UNIVERSAL
LIBRARY

OU_160139

UNIVERSAL
LIBRARY

OSMANIA UNIVERSITY LIBRARY

Call No. 551.5/G31C Accession No. 31377

Author Geiger, R.

Title Climate near the ground.

This book should be returned on or before the date last marked below.

THE CLIMATE NEAR THE GROUND

BY

PROF. DR. RUDOLF GEIGER

Professor of Meteorology, University of Munich and Director of the Meteorological Institute

A TRANSLATION

BY

MILROY N. STEWART
AND OTHERS

OF THE SECOND GERMAN EDITION OF
DAS KLIMA DER BODENNAHEN LUFTSCHICHT
WITH REVISIONS AND ENLARGEMENTS
BY THE AUTHOR

PUBLISHED FOR

BLUE HILL METEOROLOGICAL OBSERVATORY
HARVARD UNIVERSITY

BY

HARVARD UNIVERSITY PRESS
CAMBRIDGE, MASSACHUSETTS

1950

COPYRIGHT, 1950, BY THE PRESIDENT AND FELLOWS OF HARVARD COLLEGE

PRINTED BY THE HARVARD UNIVERSITY PRINTING OFFICE
CAMBRIDGE, MASSACHUSETTS, U.S.A.

CONTENTS

PREFACE TO THE FIRST EDITION 1927

I was introduced into the realm of microclimatology by Professor A. Schmauss. When he put me in charge of the organization and direction of the Bavarian special network for investigation of the air layer near the ground; and later when I had to make two greater open-air investigations in the realm of forest meteorology, I had the opportunity of getting in closer touch with people dealing in forestry, moor cultivation, and agriculture. On this occasion I got acquainted with the difficulties, everywhere met, in the practical application of the results of climatological research. This problem of application is indeed not new, and several valuable contributions have already been made (I hope that this book will prove this fact); but a systematical study has not been undertaken as yet. The practitioner has neither time nor opportunity to look for the respective papers from the vast meteorological literature. When, therefore, I was invited to write a "Climate of the Air Layer Near the Ground," I was glad of the opportunity to attempt a first survey of microclimatological problems.

With this book I hope to be able to give my best thanks to those above mentioned men for the manifold suggestions which I have received from them; especially the scientists and practitioners in forestry, highly interested in microclimatological problems. It is also with the greatest pleasure that I express here my sincerest thanks to Professor Schmauss for his constant and unselfish furtherance of my work.

DR. RUDOLF GEIGER
Meteorologist at the Bavarian Landeswetterwarte
Meteorological Observatory of Bavaria
and
Privat Dozent at the University of Munich

Munich, July 1927

FROM THE PREFACE TO THE SECOND EDITION

During the past decade, microclimatology has experienced an expansion and development to an unexpected degree. Since the appearance of the first edition, some thousand new works have been published by meteorologists alone. Perhaps more fruitful still has been the progress of microclimatic research methods in allied sciences, in the habitat teaching of botany, in forestry and gardening, in zoology, biology and medicine, in agriculture, room planning and arrangement — even in the technical aspects of traffic and construction work.

The book was out of print for several years, so that it required complete revision. Hardly any sentences are left of the first edition. Nevertheless it is the same old book, for the purpose is unaltered. The plan and operation of microclimatology were there stated and the results so far attained in this new and promising field of research were presented. But while the attempt of 1927 was justified by the novelty of the goal, the rounded picture of the new field of endeavor can only now be completed. The subtitle of "Textbook of Microclimatology" has seemed justified.

Certain necessary generalizations have been made as compared with the former edition. Section IV takes up the influence of the soil, including the air layers in proximity to water and snow. Chapter 36 deals with the relations between the animal world and microclimatology. The relations of man to the microclimate are not merely touched on but are systematically treated in Chapters 37 through 41.

Everything has been deleted which did not strictly pertain to the theme. The question of frost damage occupied the whole of the last section in the first edition. Since then there has appeared, in 1940, the work of O. W. Kessler and W. Kaempfert in "Protection against Frost Damage," which gathers up all old and new research and experimentation in this field. When, on page 7 of this publication it is said of the "The Climate near the Ground" that it has "brought the whole frost problem into the front rank," it has done its best for this question and can therefore rest. Whoever is especially concerned with the fight against frost should refer to the listed publications of the Weather Service. In the new edition, consequently, only the necessary survey of the problem within the compass of general microclimatology has been given in the two last chapters.

I have taken especial pains with the references. It is particularly important that the reader should have easy access to original sources. Those of experience know how much trouble this entails. The literature cited may still have omissions particularly in the border provinces in spite of every precaution. I hope such will be brought to my attention. The extent of the references here given could be set at about 800 items, for there are several separate lists available which I need only mention — namely, that of H. Lettau on the problem of mass exchange, of A. Kratzer on City Climate, of B. Huber on the heat economy of plants, and that of O. W. Kessler and W. Kaempfert on the frost question. In this way 1200 other works have been included without particular mention. On the whole, a considerably enlarged content of the second edition remained unavoidable. Both editor and publisher have, in spite of wartime conditions, made possible a publication suited to the problem, especially in the tripling and bringing up to date of the illustrations, for which I wish to express my thanks here.

RUDOLF GEIGER

Eberswalde, June 20, 1941
Meteorological Institute of the Forestry College

PREFACE TO THE TRANSLATION OF THE AMPLIFIED SECOND EDITION

The first edition (1927) was translated by Prof. John Leighly and proved to be very useful. At his suggestion the Air Force Weather Service obtained a copy of Dr. Geiger's second edition at the end of the war: only one copy could be found. They were pleased with the suggestion that a translation be prepared, but they were not in a position to undertake it. Prof. Leighly could not then translate the new edition, so the Air Force Weather Service kindly loaned it to the Blue Hill Observatory.

About this time, Mr. Milroy N. Stewart, of the Rochester, N. Y., branch of the American Meteorological Society, indicated a desire to make the translation; so the book was sent to him, anticipating arrangements with the Alien Property Custodian for publication by the Blue Hill Observatory. Dr. F. A. Brooks, of the University of California, Davis, California, used a portion of his sabbatical leave in 1947 for checking the heat transfer parts of the translation. We are further indebted to Prof. Brooks, and also to Prof. James E. McDonald, Dept. of Physics, Iowa State College of Agriculture and Mechanic Arts, and Prof. H. C. S. Thom, University of Maryland and U. S. Weather Bureau, for critically reading proofs of the entire book. The expense of publication was borne by the Frank Hagar Bigelow, Class of '73, Fund for Publication and the Geophysical Research Fund, both of Harvard University. The main burden of preparing the edition for publication, including clarification of obscure passages and some other translation, was carried by Dr. Wallace E. Howell, who edited the translations and supervised or himself personally performed the numerous minor operations required.

A considerable and widespread interest in the translation of Dr. Geiger's book developed, and many purchase requests were received. Then, shortly before the translation of the second edition was finished, word was received that a third edition had been prepared and was awaiting paper for publication in Germany. At this time, Dr. Geiger had been "found." He kindly consented to supply additions to the second edition that would make it possible for us to make our translation the virtual equivalent of the third German edition. Mrs. Victor Conrad translated the additions and prepared the indexes.

The photographic department of the Fogg Museum of Art, Harvard University, photographed all the illustrations in the second edition. Miss Ann E. Reiter translated the legends. The Eastern Engravers, Inc. performed the meticulous task of substituting English for German words on the numerous diagrams. Mrs. Barbara Glick and Miss C. M. Whalen typed the translation, the table headings prepared by Dr. Howell, and all but the largest tables.

Milton, Mass. CHARLES F. BROOKS
August 1950

INTRODUCTORY CHAPTER

The Microclimate and Microclimatic Research

When regular meteorological observations began in Europe in the second half of the 19th century, it soon became evident that the results obtained therefrom were influenced by the exposure of the meteorological instruments. In the larger countries, therefore, comprehensive series of experiments were soon carried out to determine the most suitable exposures. After much trouble, they standardized on the meteorological shelter which is today familiar to everyone. Within this shelter, the measuring instruments are 1½ meters — most of them, 2 meters — above the ground. This great distance was chosen because at a lower position the variations of the ground, the physiographic peculiarities, and the nearby surroundings, were too evident. The air layer adjacent to the ground was a zone of disturbance which should be avoided.

The high location of the instruments made it possible that the data of the meteorological stations could be regarded as valid for a larger surrounding district. The results of the points of observation — separated by 10, 100 and even more, kilometers — made a unified picture when pieced together. The general features of the climate as a whole could be recognized for a given neighborhood or a given country. This climate was therefore called the "large scale climate" (or, using the Greek term, the "macroclimate").

In the meteorological year-books which the civilized countries issue regularly, in the works on climatology and in descriptions of climates in geographical works, it is this macroclimate which is treated. The macroclimate of Germany is described in a recent exhaustive production in several volumes which the Imperial Weather Service is publishing, entitled "Climatic Information on the German Empire."

With the progress of science and especially with the increasing use of scientific data for economic purposes, new needs have arisen. The plan of the meteorological year-books is no longer sufficient. Indeed they have even proved misleading when used without further practical precautions. For instance, the number of frost-days, as published in the annuals, give a false picture of the frost danger to agriculture. The published maximum temperatures are not authori-

tative in determining the heat available to grapes on the vine. It was soon found that all plants have their lives conditioned by that very zone of disturbance which had been so meticulously avoided in meteorological observations. Within this zone the prevailing climatic conditions are different from those at 2 meters height. Thus arose the question concerning the climate near the ground.

The macroclimate is of direct significance to man, who goes upright, breathes at a height of 1½ meters and is continually changing his environment. The lower plant, however, bound as it is to one location, is particularly dependent on the disturbed ground layer at that period in its growth when it is most sensitive — its youth. Sometimes, therefore, the macroclimate is called the "climate of man"; the ground layer climate, the "climate of plants." These two designations are illustrative but they do not define.

By the expression "near the ground," we mean in this book, all that is not more than 2 meters from the earth's surface. By the "ground air-layer" therefore, we mean the lowest 2 meters of the atmosphere. This distance serves temporarily to give the reader some idea of the magnitudes involved. Later we shall have more to say on the subject. In this use of the words "near the ground" we differ from the aerologists, who think in terms of such a vast atmosphere that for them the lower thousand meters are "near the ground."

The difference between the climate near the ground and the macroclimate consists essentially in the proximity of the earth's surface. As the lower limit of the atmosphere, this surface plays an important role in meteorology. The heating and cooling of the atmosphere in the course of the day and according to seasons, takes place in general through it as an intermediary. By evaporation from it, water vapor is given to the air — returning to it again as rain and snow. It acts as a brake on the winds which pressure differences initiate. It is therefore no wonder that the ground air layer shows peculiar climatic characteristics. They will be described and explained in the first part of this book.

But there is something more. While, in the upper air contrasting conditions which occur are immediately equalized, in the air near the ground they may continue to exist almost side by side, for every convective movement which is initiated is tied up by friction on the surface. Horizontal contrasts are added to vertical. Great climatic differences can result within the shortest distances by reason of the kind of soil, its form, the plants growing thereon, variable shading or sunniness, different wind protection, and many other circum-

stances. G. Kraus coined for it the apt description, "Climate in the Least Space." This term is somewhat too ceremonious for general usage. In its place the word "microclimate" is used today. The best definition of microclimate is, conversely, "climate in the least space." Microclimatology is the science of the microclimate.

With the rise of microclimatological research, many new expressions have come forward such as: "local climate," "peculiar climate," "miniature climate," etc. They all mean the same as "microclimate" and are best forgotten. If one German word can describe the microclimate, that word is "Kleinstklima," but nobody likes to pronounce these five harsh consonants in succession. The word "Kleinklima," which might be suggested, is objectionable on other grounds.

R. Geiger and W. Schmidt (*6*) (the italic figures refer to the literature cited at the end of the book) have made an attempt to introduce unified terminology in microclimatology. This attempt has resulted in confusion rather than clarification. According to their proposal the word "Kleinklima" should occupy an intermediate position between the expressions "macroclimate" and "microclimate" and has been used in this sense in several places. It now appears to me an unavoidable necessity, sooner or later to settle on such an intermediate term; the real need is becoming more apparent. The designation "Kleinklima" is, however, quite unsuitable, for to avoid the distasteful word "Kleinstklima" or the adjective "Kleinstklimatisch," "Kleinklima" has been used in numerous publications as synonymous with microclimate.

The word "Kleinklima," consequently, having two different meanings, has become useless. H. Scaëtta (*17*) has made an excellent suggestion: Between the macroclimate and the microclimate should be the "mesoclimate." I was very much tempted to make the description clearer by the introduction of this new term. But it is still too soon for that and the danger is too great that even this expression would be misunderstood and misused. The terms "mesoclimate" and "mesoclimatology" appear therefore in neither title nor inscription. The attempt has merely been made to inform those same readers who will actually read the book, in the proper places, in order to lay the basis for future developments.

In this book everything which does not belong to the macroclimate and which concerns the climate of a very small space, is brought together under "microclimate."

It is no accident that microclimatology has been developed in Germany. The lack of living space, and the consequent necessity of

getting the utmost out of the earth, has favored this development. If we look back over the history of microclimatology it is no less noteworthy that it was a scientist who, out of purely scientific interest, first concerned himself deeply with microclimatic problems. It was the Würzburg botanist, Gregor Kraus (1841–1915).[1] By the publication in 1911 of his book (*12*), "Boden und Klima auf kleinstem Raum," he became the father of microclimatology, although he did not use that word himself. Not a practical application but basic research in the fundamentals of the science guided him in his first investigations in the Wellenkalk district of the Main at Karlstadt. "Having undertaken the task," he writes, "I realized that I stood here alone, and that, to accomplish something permanent, the very foundation would have to be laid 'in the egg' and everything done for the first time. From the first undertaking, working backward toward more solid ground — this is the way the material in Part I was assembled." These words, applied first of all to his work on soil conditions in smallest space, apply equally well to climatic conditions in the same limited space.

If G. Kraus became known as the father of microclimatology, it was because he was the first to see the problem clearly, to formulate it and to attack it. Along with him many others have pioneered, especially Th. Homén, whom V. Rossi (*211*) calls the "Founder of microclimatology in Finland." Yes, as we look back, we are able to find references to microclimatological problems in early times as, for example, B. H. Grimm (7) quotes some such sentences from the chemical letters of Justus von Liebig. Thus it is with all newly developing scientific fields. We hope that the factual information in this book will direct each co-worker in microclimatology to the right place.

Microclimatology occupies a special position in the realm of the natural sciences. As part of climatology it pertains to the great technical province of meteorology and is, systematically, mostly indebted thereto. At the same time it is also so closely involved with numerous kindred sciences that plenty of suggestions and worthwhile projects originate in those fields. Among these, botanists are some of the first to be mentioned — particularly ecologists. Representatives of forestry and agriculture have cooperated. The zoologists, too — among them, the entomologists in particular — find in microclimatology the habitat condition for the favorable or un-

[1] His biography by H. Kniep is to be found in Berichte der Deutschen Botanischen Gesellschaft, Vol. 33, pp. 69–95, 1915.

favorable development of animals. In many questions the physician is interested; in many others, the geographer. Even the technician and the tradesman come up against climatic peculiarities in restricted spaces — in street construction, railroad building, house construction, and the establishment of communication systems. Thus microclimatology affords an exceptionally fine example of a scientific community of effort. While formerly the extent of science has led to the leveling out of research, and its depth to undue specialization, in microclimatology the two formerly contradictory extremes seem to join hands. As a special science it can and must deepen; being rooted in a great number of technical fields it possesses at the same time an enlivening and enriching breadth.

PART ONE

Concerning the microclimate existing near the ground by virtue of its proximity to the ground surface.

In order to learn about the climate near the ground, we investigate in the first part of the book the influence which the ground exerts on the climate of the boundary layer of air next to it, to a height of about 2 meters. In order to begin with the simplest conditions, we shall think first of a completely flat plain, free of plant growth. Section I will establish a fundamental point of view regarding the role played by the ground surface in the heat economy of the atmosphere and hence of the layer of air next to the ground. In particular, the manifold ways and means by which heat moves to and from the ground will be discussed.

Section II shows the consequences of these with respect to the temperature relationships, which in the layer of air next to the ground are so completely different from those in the realm of the macroclimate. The other weather factors, namely vapor pressure and relative humidity of the air, wind velocity, dust content, visibility relationships, and so forth, are treated in Section III.

Even omitting the influences of topography, vegetation, and buildings, which are to be considered in Part Two of the book, the kind of ground yet has significance for the climate near the ground. Not only the material, the water content, and the color of the ground must be considered, but furthermore above a water surface or a snow surface the air layer next to the surface has especial characteristics. These questions are the subject of Section IV.

SECTION I

HEAT EXCHANGE NEAR THE GROUND

CHAPTER 1

Midday Heat Exchange at the Ground Surface
The Incoming Radiational Type

At the upper limit of its atmosphere the earth receives a vertical solar radiation amounting to about 2 calories per square centimeter each minute. This value is called "solar constant." At European latitudes normal incidence does not occur. There the horizontal surface receives at the border of the atmosphere only a portion of the solar constant. When this radiation penetrates the earth's atmosphere it suffers a series of losses.

Fig. 1 shows the heat exchange at noon of a summer day in Germany; the width of the arrows in the figure give an idea of the relative amounts of the transferred heat totals. First, we consider only the heat transport caused by short wave radiation (length of waves below 1 μ) (in Fig. 1 widely dotted stripes).

A considerable portion of the enormous incoming sun energy is reflected by the surface of the clouds and is ineffective concerning the heat economy of air and ground. As an average for the northern hemisphere and the year, this amount is 33% of the incoming radiation. In the atmosphere another portion of radiation is scattered in all directions diffusely by the air molecules themselves and by substances suspended in the atmosphere (dust, plankton). The radiation does not suffer a loss in the true sense of the word but only a deflection from its original direction. But because a portion of the scattered radiation goes back to universal space (Fig. 1) also this portion is eliminated with regard to the terrestrial heat exchange. Reflections from clouds and diffuse scattering into universal space make together 42%. The reflecting power (albedo) of the earth, therefore, is 0.42; for the inhabitant of universal space the earth looks about as bright as Venus does for our eyes.

The third loss is the absorption of radiation caused by ozone, water vapor, and carbonic acid; this is a true loss in that the radiation energy is used to increase the temperature of the absorbing

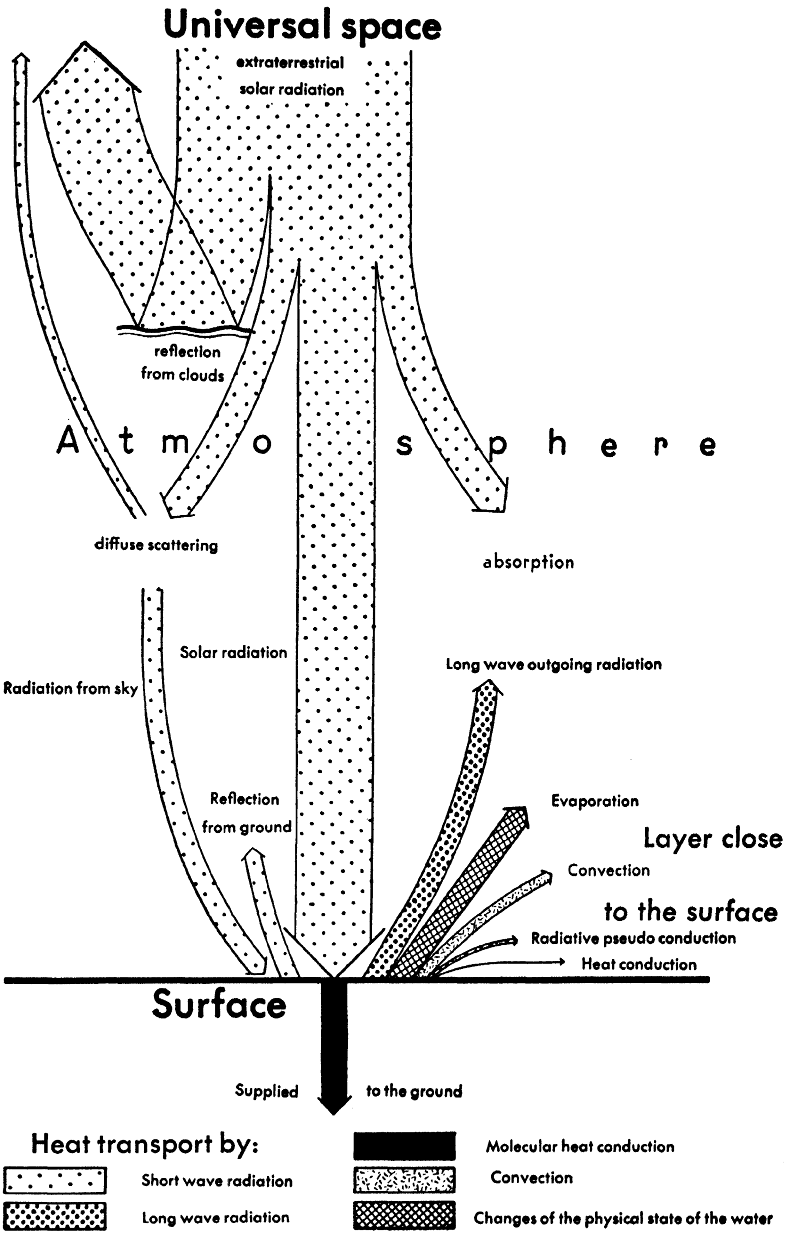

FIG. 1. Heat exchange at noon for a summer day. (The width of arrows corresponds to the transferred heat amounts)

gases and, therefore, is eliminated from the insolation economy. What happens with this portion is not discussed in this book.

Despite the enormous distance the sun rays have to pass through from the limit of the atmosphere down to the bottom of the atmosphere, a mighty radiation flux penetrates down to the earth's surface partly as direct sun radiation, partly as scattered radiation from the sky. The two together represent the main portion of the solar heat at the disposal of the heat economy of earth and air. Wherever this immense energy current strikes upon the surface of the solid ground the radiation cannot penetrate this obstacle. A portion is reflected from the surface. Most of it is absorbed, changed into heat, and serves to raise the temperature of the ground.

The earth's surface, then, plays the most important part in midday heat exchange, but the layer of air next to the ground is that part of the atmosphere whose temperature relationships are most directly determined by the relationships of the surface itself. Observations of this lowest layer of air are therefore indispensable to studies of heat transfer.

If we glance back over the history of meteorology, we find that the importance of the air layer adjacent to the ground led to the first observations in this province. The study of this lowest layer thereby became a branch of general meteorology, the physics of the atmosphere. Only later did the climatological side gain attention, when experience in practical farming made people realize the very different climate to which young plants are subjected close to the ground.

It will first be necessary to obtain actual values for the amount of radiation reaching the earth's surface at noon, here in Germany. For this purpose we shall use the measurements made at Potsdam from 1907 through 1923 as published by W. Marten (*34*) and thoroughly analyzed by J. Schubert (*39*). The results are presented in the accompanying table, which is divided, on the one hand, as to (A) clear or (B) partly cloudy weather, and on the other hand as to whether the receiving surface is perpendicular to the radiation (normal radiation) or horizontal. In each case the value given is for 12 noon even when, with a cloudy sky, the highest radiation value occurs during the forenoon.

When considering the microclimate at high altitudes, for example, the living conditions of alpine plants, it must be remembered that solar radiation increases with height above sea-level. The increase is most rapid in the lowest, dust-filled air layers. The higher we go, the less the gain in radiation with increased height. W. Mörikofer

TABLE 1

INCOMING SOLAR RADIATION IN CAL/CM^2, MIN AT MIDDAY DURING THE MIDDLE OF THE MONTH

(Total and Horizontal Radiation) (After measurements in Potsdam 1907–1923)

	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
A. Clear Day												
Total Radiation (that received by a surface normal to the radiation) ..	1.014	1.120	1.121	1.275	1.278	1.274	1.196	1.169	1.220	1.167	0.987	0.967
Horizontal Radiation (that received on a horizontal surface)	0.287	0.471	0.649	0.937	1.065	1.113	1.027	0.918	0.796	0.569	0.324	0.240
B. Under Condition of Average Cloudiness												
Total Radiation	0.264	0.325	0.437	0.536	0.626	0.650	0.574	0.573	0.573	0.467	0.266	0.242
Horizontal Radiation ...	0.075	0.137	0.253	0.394	0.522	0.568	0.493	0.450	0.374	0.228	0.087	0.060

(*35*) gives the following values for the noon radiation of a cloudless day in January, based on measurements at Davos, St. Blasien and Karlsruhe.

Altitude	100	500	1500	4000 m
Radiation (calories per square centimeter and minute)	0.8	1.2	1.4	1.6

Similar data for all the months and for altitudes from 390 to 1577 m may be found in F. Lauscher (*33*).

In the mountain ranges still more than in the lowland, the climate of the layer near the ground is in greater contrast to the macroclimate on account of increased radiation and a simultaneous decrease of air temperature. The saturated flower color of the alpine plants prove this fact. Unfortunately, systematic observations in this direction are still lacking.

The radiation-exchange is not fully described by the treatment of short wave radiation. The sun radiation is accompanied by the outgoing radiation, most effective in the long wave portion between 4 μ and 32 μ. The amount of this radiation loss from the earth's surface is also plotted on Fig. 1. In comparison with the enormous incoming radiation, the long-wave outgoing radiation plays only a small role. The balance of radiation of the earth's surface is strongly positive at noon in summer. At night, however, when no radiation from the sun exists, it is just this long-wave outgoing radiation which controls the exchange of radiation. In the following chapter we shall deal with this phenomenon when discussing the radiation balance by night.

The temperature conditions of the layer near the ground are determined by the immense amount of heat which the surface of the ground absorbs. In summer, this surface is heated in our region up to 60°C, sometimes to 70° and 80°; (see Chapter 13). The temperature of the surface would be increased even much more if a heat loss — caused and maintained by the temperature contrasts — did not take place upwards and downwards. Fig. 1 shows direction and amount of these various heat currents. One portion of the heat is conducted from the surface to the deeper layers of the ground as is further described in Chapter 3. The greater portion serves to heat the air layer near the ground and thus, indirectly, to heat the atmosphere. Partly also here, heat conduction is effective, but as can be seen from the small arrow of Fig. 1 it does not play an important role as far as quantity is concerned. Primarily, convection and

radiative pseudo conduction come into consideration. These are phenomena which are discussed concerning their origin and effect in Chapters 4 and 5. Furthermore, the ground loses much heat as a consequence of evaporation since the surface is deprived of 600 gcal if one gram of water evaporates; this is an amount of heat which would suffice to heat 6 g water from 0°C to the boiling point.

From the significance of the earth's surface for heat exchange it can be concluded that the highest temperature at about noon is at the

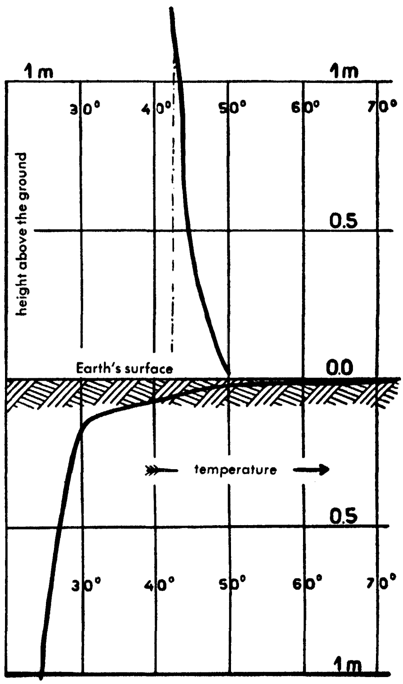

FIG. 2. The incoming-radiation (insolation) type. (Tucson, 21 June 1915)

boundary between ground and air; starting from here, the temperature decreases upward and downward. This kind of temperature distribution at noon time is called "*Incoming Radiation Type.*" The real character of this type will be demonstrated by an extreme example.

Fig. 2 gives the temperature distribution which J. G. Sinclair (*40*) observed at the Tucson Desert Laboratory on June 21, 1915, at 1 P.M. As we approach the ground from above, the temperature

rises continuously and at an increasingly rapid rate. At the surface there is a temperature discontinuity between air and earth. The surface itself possesses the highest temperature, not measured here, but in any case far above 71.5°, the measurement at a depth of 4 mm in the ground. In the first 10 cm of earth the temperature decreases with extraordinary rapidity, so that at a depth of 7 cm it is already several degrees below the air temperature. The effect of the time of day, the temporary noon-time heating, extends to a depth of only about 10 cm, as the break in the temperature curve indicates. In the lower earth layers the temperature falls again slowly.

Extremely high midday temperatures are therefore, as the illustration indicates, limited to the air and soil layers immediately bordering the earth's surface. Even under our mild climatic conditions the same holds true, though to a lesser extent. In the consideration of the daily march of temperature (Chapter 8) further examples are given of the temperature distribution with an incoming radiation pattern.

While the laws of heat movement in the ground have long been known, the rapid decrease of temperature upwards in the lower air at midday is of particular interest. P. T. Smoliakow (*41*) has recently treated the question theoretically, especially in reference to microclimatology. The following general facts have been established:—

If dry air is moved up or down in the atmosphere adiabatically, i.e. without the addition or subtraction of heat, its temperature changes. In moving upwards it comes into a region of lower air pressure, its volume increases, and work is thereby performed, which must draw adiabatically on the heat energy of the air itself. It therefore becomes cooler. Descending air, on the other hand, becomes warmer. Thermodynamics teaches that this temperature change amounts to 1°C per 100 m difference in altitude.

If the "adiabatic gradient" of 1°C per 100 m prevails in the atmosphere, an air parcel moving either up or down will at all points find the same temperature as it has itself and the same pressure as well. It is in neutral equilibrium.

If the temperature decrease is less than 1°C per 100 m, a rising air parcel will come into warmer surroundings. It will be heavier than the surrounding air and will therefore return to its original position. The air is in stable equilibrium. If the temperature decrease, however, is greater than 1°C per 100 m, so that the gradient is, as we say, "super-adiabatic," a rising air parcel must reach colder

surroundings and its upward movement is accelerated. Unstable equilibrium prevails.

These thermodynamic considerations are based, however, on two assumptions. First, the air parcels put out of balance must have the necessary freedom of motion so that they can obey the changed conditions. Second, the above considerations are valid only for isolated air parcels ascending and descending respectively within an air mass which is essentially not influenced by the processes which cause the instability of the air parcels. H. Wagemann drew my attention to this fact. Neither assumption holds true for the layer near the ground. There, heating from below is so strong and uniform above great areas of the surface that superadiabatic gradients become regular in the presence of intense incoming radiation.

TABLE 2

Month (1925)	Feb.	April	June	Aug.	Oct.	Dec.
Greatest difference of temperature in °F between 1.2 m and 7.1 m	2.8	2.9	3.6	2.9	2.4	1.4
Calculated lapse rate (°C per 100 m)	26	27	34	27	23	13

In the free atmosphere superadiabatic gradients not only occur rarely but they surpass the amount of 1°C/100 m only by a few tenths of centigrade degrees. Approaching the ground these conditions change. Observations by N. K. Johnson (*182*) in England in 1925 yielded the following maximum values of the difference of the true air temperature at the heights of 1.2 m and 7.1 m:

These values occurred throughout at hours between 11 A.M. and 2 P.M. Even at these heights above the ground each month shows the formation of a temperature gradient which is from ten to thirty times as great as the adiabatic.

There remains, however, the fact that the air layer next to the ground is at this time unstable in the highest degree. There are two resulting phenomena which serve to demonstrate this particular condition to every thoughtful observer. One is the formation of streaks, which we shall treat as an optical phenomenon in Chapter 12. The other is the formation of dust whirls, also called sand-devils or according to A. Wegener (*43*) "small spouts." They are such a common phenomenon and so well-recognized a sign of superheat-

ing of the air near the ground that they occupy a recognized place in the "ww group" among the international meteorological symbols.

Instability may be considered as the final preparation for an upset of stratification, with the warm air ready to eddy upward and the cold air to sink. At the ground the initial impulse which will put this overturn into action is still wanting. When, however, such an upward whirl is initiated through some outside agency, the adjacent layers are drawn into the movement and the phenomenon proceeds, borne along by the wind, affecting new layers one after another, and thus gaining strength. Immediately there begins — for some still rather obscure reason — a whirling motion which quickly intensifies and so there is formed a whirlwind with an axis which is vertical or inclined slightly forward with the wind.

This whirlwind first becomes visible when it picks up dust, sand, leaves, grass or, with further development, even stones and branches. The formation of a whirl is often easily observed. Haycocks, roadside slopes, the piles of stone along country roads, are favorite points of origin, because there the first upward movement of the heated air is favored by the shape of the surface.

I once made an observation of this sort on a scorching hot summer noon while walking on the Jura chalk plateau of the Frankish Alp (at Hetzles near Erlangen). Fig. 3 shows the conditions

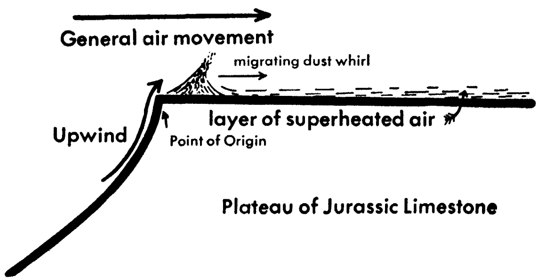

FIG. 3. The origin of a dust whirl (small spout)

schematically. Over the white, dry chalk plateau, sparsely covered with vegetation, there formed a strongly superheated layer of air next to the ground. An upset was initiated at the steep western edge of the plateau, where the vertical component of the wind introduced an upward movement.[1] A whirl started off from this

[1] On account of the tilting of the geological strata toward the east, the western rim of the Frankish Alp is the highest point of the plateau, thus favoring vertical motion in that region.

point, raising dust and leaves with a clearly audible whistling sound to a height above one's head, and moving off with the general drift of the air from the edge toward the interior of the plateau. After leaving the outer zone its behavior became unpredictable. It jumped to one side or the other, wherever favorable conditions existed for heated air to break through upward, but died out in a few minutes, over the uniform plateau. At the edge, however, the formation was several times repeated.

TABLE 3

NUMBER OF DUST WHIRLS OBSERVED 1927–1932

	Jan.	Feb.	March	April	May	June	July
In Egypt and in the Sudan	0	0	3	11	30	25	35
In Palestine and Transjordan	0	0	0	5	7	29	23
In Iraq	0	0	7	11	6	19	28
Total:	0	0	10	27	43	73	86

	Aug.	Sept.	Oct.	Nov.	Dec.	Year
In Egypt and the Sudan	26	27	5	1	1	164
In Palestine and Transjordan	34	25	5	1	1	130
In Iraq	14	18	12	0	0	115
Total:	74	70	22	2	2	409

H. Schlichting (*37*) gives a very interesting account of a whirl which came under his observation at Lübeck at 1 P.M. on a certain day in May, 1934. H. Schober (*38*) described one which originated at the boundary between a heated meadow and a shady street.

The most thorough going studies of dust whirls we find in the works of W. D. Flower (*30*) who in the years following 1927 carried out regular observations at 12 meteorological stations in the dry region between Egypt and the Persian Gulf. The following results were obtained by months for the years 1927–1932.

The large numbers in those months with the strongest radiation is evident. Just as prominent is the grouping according to time of day. Fig. 4 shows the daily march of dust-whirl frequency for the years 1926–1932 in the three above mentioned localities. Also shown is the mean temperature gradient in Ismailia for those days in 1932 on which dust whirls were observed. The increasing tendency to dust-whirl formation with increasing temperature gradient is plainly recognizable.

The dust whirls here observed had mostly a height of between

25 and 50 m. The limits were <5 and $>1{,}000$ m. Even in a region so far north as Iceland, A. Wegener (*42*) observed dust-whirls even 1,000 m in height, which were, to be sure, over vegetationless plains of black lava sand where at midday conditions are favorable for great heating of the air layer next to the ground.

According to W. D. Flower, the duration of a dust-whirl in about one fourth of all cases is less than 30 seconds. Most of them last

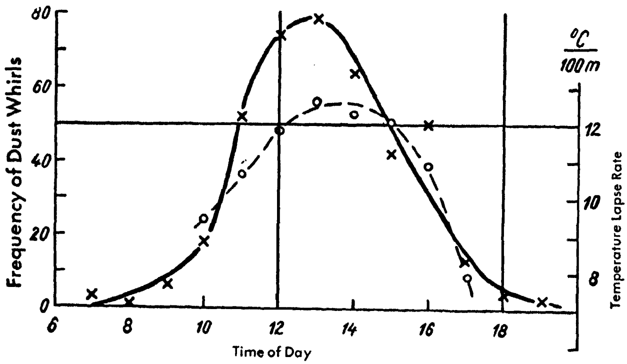

Fig. 4. Frequency of dust whirls (continuous line) and temperature gradient from 4 to 50 feet (broken line). (After W. D. Flower)

several minutes, but not over 20 minutes, at the longest. By watching pieces of paper and the like which they carried along it was determined that they whirled at the rate of 0.1 to 0.6 revolutions per second. In 175 cases the whirls turned in a clockwise direction; in 200 cases, counterclockwise. There seems therefore to be a rather indifferent distribution in this respect. When the rotation was clockwise, the course of the whirl as it died out was counterclockwise away from the wind direction, and vice versa. This corresponds to the "Magnus effect." This turning away from the course of the wind continued to the end with increasing curvature, so that in its final moment the dust whirl sometimes for an instant stood directly against the wind.

Recently F. Rossmann (*36*) has been studying the law of motion of waterspouts.

CHAPTER 2

Nocturnal Heat Exchange at the Ground Surface. The Outgoing Radiational Type

From the incoming radiational type, which is most clearly demonstrated on a hot summer day, we now turn to the opposite condition, the outgoing type, which is best seen on a cold winter night.

Solar radiation, which governs the heat exchange by day, is lacking at night. No other natural source of energy is comparable to that of the sun. In regard to the nocturnal heat exchange, we may say at once, therefore, that it must necessarily be slight in comparison with the diurnal, and that even at the most there is no such abrupt temperature contrast in a very short distance, such as occurs by day.

The heat exchange during the night is dependent on heat radiation from the surface of the earth, which is what we must now consider.

According to the Stefan-Boltzmann law of radiation, every body radiates heat with an intensity proportional to the fourth power of its absolute temperature. Since the temperature of the sun is about 6000°C, while average earth temperature at the surface is only 14°C, or 287° absolute, it is evident how weak the nocturnal heat radiation is. But its quality as well differs from that of the sun. According to the Wien displacement law, the product of the absolute temperature of a radiating body and the wave length of the most intense radiation, is a constant. With rising temperature the band of strongest radiation moves toward the shorter wave lengths. This maximum intensity of solar radiation lies at 0.5 μ, which is in the visible part of the spectrum, between green and blue. The maximum intensity of earth radiation, however, lies in the neighborhood of 10 μ, which is far into the longwave (infrared) part of the spectrum.

As we saw on a preceding page a considerable fraction of the sun's radiation is able to penetrate the entire atmosphere and reach the surface of the ground. It is otherwise with the outgoing radiation from the earth's surface. Water vapor and carbon dioxide have the property of absorbing radiation in certain bands of the spectrum, which happen to be those of long wave length. Their absorption capacity is selective. We speak, therefore, of "band" absorption or of the selective absorption of water vapor and carbon dioxide. The

fact that our atmosphere easily admits solar radiation but lets earth radiation out only reluctantly, is, as we all know, of fortunate significance for the retention of the earth's heat. It is referred to as the "hot-house" effect of the atmosphere.

According to F. Moeller (67 and also 29) only 12% of the earth's nocturnal radiation passes out to be lost in space. All the remainder is absorbed by the various layers of air, in proportion to their water-vapor and carbon dioxide content. The really difficult question of radiation exchange within the atmosphere we can pass over and, in what follows, consider only two amounts: the radiation outward from the solid ground surfaces and the total radiation of all the air layers above the place of observation, which is called the counter-radiation of the atmosphere.

If t in °C represents the temperature of the ground surface, then, according to the already mentioned Stefan-Boltzmann law (which in the strict sense applies to black bodies only) the outward radiation, S in calories per sq. cm. per min., is

$$S = \sigma\,(t + 273)^4$$

The constant σ has the value 8.26×10^{-11}. From this we get the following temperature-radiation relation:—

TABLE 4

Surface temperature of the ground (°C)	−40	−30	−20	−10	0	10
Outgoing Radiation in cal/cm², min	0.244	0.288	0.339	0.395	0.459	0.530
Surface temperature of the ground (°C)	20	30	40	50	60	70
Outgoing Radiation in cal/cm², min	0.609	0.696	0.792	0.899	1.015	1.143

When considering the nocturnal heat balance we are quite apt to attribute the strongest outgoing radiation to the wintertime. There is danger of confusing the *duration* of the radiation, which naturally is considerable during long winter nights, with its *intensity* per unit of time. As the above-given figures prove, the latter is much higher in summer; on a warm summer night it is double that of a cold winter night.

E. Hasché (58) has studied the variation in the intensity of the net outgoing radiation in the shade in the course of the day. During the night it decreased by from 7% to 8% on account of the

temperature drop. After sunrise it increased slowly and reached a maximum about sunset. From then on it decreased rapidly, reaching the general nocturnal level early in the night. In the daytime, naturally, these steps are obscured by solar radiation. They are not, however, of merely theoretical interest, for at times they play an important part in microclimatic problems.

The amount of outgoing radiation, which can be determined theoretically from the Stefan-Boltzmann law, is lessened by the counter-radiation of the atmosphere. When this is taken into consideration, we get the actual outgoing radiation obtained by measurements, which is called "effective outgoing radiation."

Since the radiation of the atmosphere is very dependent on the water vapor content of the air as well as on its temperature, the effective outgoing radiation R is also a function of the water vapor content. If p is the vapor pressure in millimeters measured near the ground, and S as before is the outgoing radiation according to the Stefan-Bolzmann law, then according to A. Ångström (*49*) the effective outgoing radiation R in calories per sq cm and minute equals:—

$$R = S(A + B \cdot 10^{-\gamma \cdot p})$$

Here A, B and γ are constants whose values are necessarily more accurate in proportion to the amount of observational data at hand. In 1935 P. K. Raman (*69*) in consideration of the work of Ångström, Asklöf (*51*), Eckel (*55*), Kimball (*60*), Ramanathan and Desai, as well as his own measurements, assigned the following values:—

$$A = 0.23, \qquad B = 0.28, \qquad \gamma = 0.074$$

The effective outgoing radiation obtained through the equation is therefore:—

$$R = 8.26 \cdot 10^{-11}(t + 273)^4(0.23 + 0.28 \cdot 10^{-0.074 \cdot p})$$

This holds for a cloudless sky since $R = S - G$ (if G represents the counter-radiation), then:—

$$G = 8.26 \cdot 10^{-11}(t + 273)^4(0.77 - 0.28 \cdot 10^{-0.074 \cdot p})$$

In these equations for R and G, the temperature t and the vapor pressure p are measured close to the ground but outside its direct influence, as is customary at meteorological stations. The tempera-

ture and especially the moisture relationships of the whole atmosphere are, however, determinative of radiation. As E. Süssenberger (*73*) recently stated, the observed values of t and p are only assumed values for the whole atmosphere, representing a normal distribution of temperature and vapor pressure with height. The variable impurities in the air are, as F. Krügler (*61*) points out, not considered at all; only with this understanding can the above given equations be used. Since, however, it is only very seldom possible to get observational meteorological material from the higher air layers and since it is usually a question of the more easily obtained ground values, the equations have the very practical value that with their aid we can in the easiest way get an idea of the magnitude of the effective outgoing radiation or counterradiation which prevails.

For general use I have recalculated the outgoing radiation value R, using the above-given constants. Fig. 5 shows the result. It indicates that the effective outgoing radiation is in the first approximation proportional to the relative humidity, for the corresponding curves are nearly at right angles. This agrees well with the findings of many authors, e.g. O. Eckel (*55*) that outward radiation is "independent" of temperature (i.e. when the relative humidity remains approximately constant). Below a certain limit, which is about 0.15 calories per sq cm per minute, outward radiation does not decrease (limited by the 100% line.) With low temperatures such as those in the polar regions and in central Europe in the winter, the possible range of fluctuation of outgoing radiation is quite small on account of the steady low humidity. The greatest range is afforded by high temperature with rather low humidity. This is the upper, right-hand area in Fig. 5; it corresponds to a desert climate or, with us, to a spell of dry midsummer weather.

The values of Fig. 5 are probably a little too high. For the layer near the ground H. Philipps succeeded in computing the very complex processes of outgoing radiation. The basic theoretical paper of Philipps appeared in 1940. His results have led to an equation for outgoing radiation and back radiation which corresponds essentially with Ångström's empirical formula; thus, its theoretical meaning is explained. The constants A, B and γ have the values 0.220, 0.148, and 0.068. Only B shows a difference worth mentioning. This difference indicates that according to the theory, the water vapor plays a smaller role than in Ångström's formula. Using the constants of Philipps we get also somewhat lower values for outgoing radiation

than are shown in Fig. 5; this is also verified by the more recent observations. F. Krügler (*61*) found even 17% lower values than those resulting from Ångström's formula. As for the amounts of outgoing radiation given in Fig. 5, we assumed that the sky was cloudless. In the presence of cloudiness the back radiation from

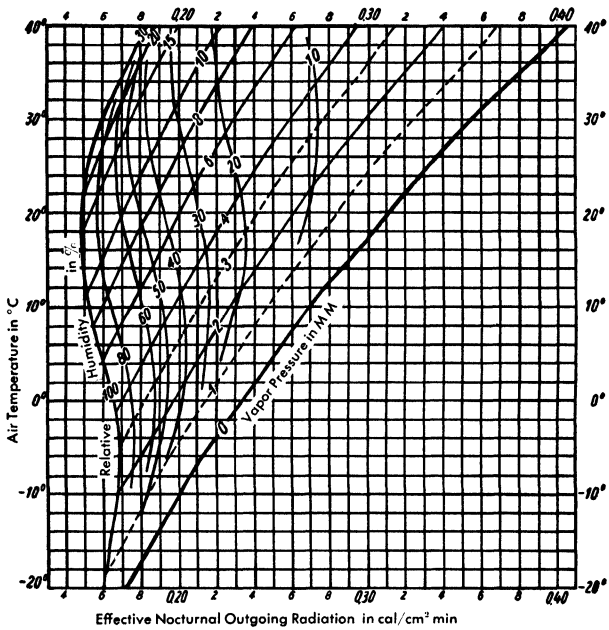

FIG. 5. Dependence of the effective outgoing radiation (R) on temperature (t) and water vapor content (p, in mm, f in %)

the lower surface of the clouds must be considered, especially in the not-absorbed portions of the spectrum where, previously, entirely uncompensated outgoing radiation existed. The back radiation is increased, the effective outgoing radiation decreased.

If R_W is the outgoing radiation at cloudiness W ($W = 0$, cloudless; $W = 1$, overcast) then, according to the observation of Ångström (*330*) and S. Asklöf:

$$R_W = R(1 - k \cdot W).$$

k is a constant which depends upon the kind of clouds, height of the ceiling and temperature in this height. According to A. Defant (*53*) k can be considered as the ratio of the difference of the effective outgoing radiation with overcast sky on the one hand and the effective outgoing radiation with cloudless sky on the other hand.

In order to use the equation in practice, one may either consider the clouds according to their kind and elevation; R. Meinander (*66*) employs the following mean values:

with low thick clouds	(Ac, Sc, Ns, St)	$k = 0.76$
with high thinner clouds	(Ac, As, Cs)	$k = 0.52$
with thin Ci veils		$k = 0.26$

or one may use the relationship between the height of the lower cloud boundary and the value of k which was found by H. Philipps (*68a*) by theory and measurement:

ceiling (km)	1.5	2	3	5	8
k	0.87	.83	.74	.62	.45

In this respect Fig. 6 contains more recent observational results. The thin broken straight lines are valid for the three kinds of cloudiness according to Ångström-Asklöf formula. Plotted on the heavier curve are the results which F. Lauscher (*62*) derived from measurements of nocturnal radiation made from Oct. 10 to Dec. 17, 1927, at Steiermark on the Stolz Alpe (elevation 1160 m). He calculated for different group averages of cloudiness the average observed outgoing radiation. His values are given in Fig. 6 as hundredths of the radiation value with a cloudless sky. High, thin sheets were omitted.

The curve shows very clearly the increasing rapidity with which radiation diminishes as cloudiness grows. At first the curve coincides closely with the straight line representing high clouds, for very slight nocturnal cloudiness is usually mostly cirrus in type. A medium amount of cloud corresponds to a middle-height cloud. With an entirely clouded sky, the clouds are commonly quite thick. In the case of fog the radiation was reduced 7 to 8% (0.011 calories per sq cm per minute).[2]

Fig. 6 can therefore be used in conjunction with Fig. 5 in order to estimate the magnitude of the effective nocturnal radiation out-

[2] The change of effective outward radiation with the height of the lower cloud boundary in the case of thick clouds was mentioned in 1936 by A. Ångström (*50*) as a result of observations at Stockholm, 1923–1933.

ward, under specified conditions of temperature, humidity and cloudiness.

The considerations thus far adduced *assume* outgoing radiation to the whole sky hemisphere. For many problems of microclimatology it is necessary to know the radiation toward certain parts of the sky. Here we can learn from the work of P. Dubois (54), F. Linke (65), E. Süssenberger (72 and 73) as well as L. A. Ramdas and collaborators (71).

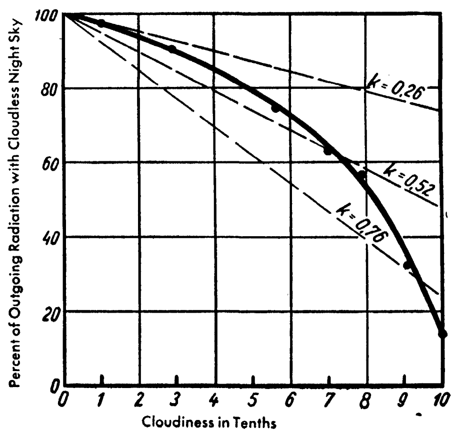

FIG. 6. Dependence of the effective outgoing radiation on cloudiness (Theory and observation)

Radiation is strongest toward the zenith, because the atmosphere is of least thickness in that direction. The more the radiation recorder is inclined to the horizon, the more effective is the counter-radiation. Directly toward the horizon outgoing radiation is zero. But there is still the dependence on the water vapor content of the air. If Z is the zenith angle and R_O the radiation toward the zenith, then the radiation R_Z toward the direction Z is, according to F. Linke:—

$$R_Z = R_O \cdot \cos \gamma Z$$

with the exponent γ dependent on the vapor pressure p according to the simplified equation:

$$\gamma = 0.11 + 0.034p$$

The following table gives values which F. Linke assembled from the data of P. Dubois.

TABLE 5

Relationship of Effective Nocturnal Outgoing Radiation to Zenith Angle Z and Vapor Pressure p (mm).

(Outgoing Radiation toward the Zenith = 100)

Vapor pressure p	Zenith Angle Z							
	0	20	40	50	60	70	80	90
3	100	99	94	90	83	72	65	0
6	100	98	93	89	81	68	47	0
8	100	97	92	86	77	63	39	0
10	100	96	89	82	73	58	34	0

If parts of the sky are screened off, this of course affects the magnitude of the effective radiation to a marked degree. Under a tall tree standing by itself, the very "coldest" parts of the sky are obscured. It is therefore easily understood that a pine or a single birch can afford frost protection on quiet nights when radiation is the chief determinant of temperature.

K. Brocks (52) measured night temperatures in narrow furrows with various angles of side slope. Here, of course, not only radiation but heat conduction has a part, yet the measurements are of interest in this connection. The temperature of the nocturnal minimum increased with the steepness of the slope. He found:

TABLE 6

with an angle of slope of	15°	30°	45°	60°	75°	90°
in the mean of 138 nights 1937	6.23	6.27	6.34	6.44	6.59	6.67
in a particular case (24/V/37)	6.6	6.6	7.0	7.3	7.5	8.1

The stream of heat (radiant and conducted) from the layers of soil cut by the furrows produced heat protection. Only when snowfall shut off the ground temperatures did the reverse temperature distribution enter and then not as a consequence of radiation but of what we shall treat in Chapter 18 as the flow of cold air.

Often the problem arises in microclimatology to determine, with a certain form of horizontal screening, how much the outgoing radiation toward the sky will be thereby reduced. F. Lauscher (*63*) has developed general methods for this purpose. From the abundance of calculated data we shall give only a few often noted examples. The first row of figures in the following table gives the radiation M from a horizontal plane in the deepest part of a basin for different slope angles (β). The outgoing radiation M is given in

percent of the simultaneous radiation from an open exposure. The calculations are based on a vapor pressure of 5.4 mm. In the second row of figures the radiation from a horizontal plane at the bottom of a valley is given as T. The valley has mountains on both sides, up to the angle of elevation β; its bottom having further a straightaway course without a grade. The values for T can be used for radiation in the middle of a straight street, a forest cutting and so forth.

TABLE 7

β:	0	5	10	15	20	30	45	60	75	90
M	100	99	98	95	91	79	55	28	8	0
T	100	99	98	98	96	90	75	54	28	0

For the microclimate in the mountains it is desirable to know the dependence of radiation on altitude also. In this direction too it is Ångström who has been the pioneer, with his observations in Lapland, Algiers and California. In general it may be said that with increasing altitude the mass of air above the place of observation rapidly decreases. In consequence, the counter-radiation also diminishes while the effective outgoing radiation increases. This increase, however, is partially offset by the fact that the temperature falls with height. There still remains an increase with height of heat loss through outgoing radiation, just as we have determined a gain in heat received by day. The microclimate of high levels is consequently not only more extreme in its higher heat reception by day, but also in its greater heat loss at night.

On page 79 of "Dynamic Meteorology" by H. Ertel (56) there will be found a sketch showing the change of effective outgoing radiation with altitude, applicable to all high levels such as are of concern in mountain microclimatology. It increases slowly at first, then more rapidly. In the first 3,000 m the change is so slight that it may be almost neglected. F. Lauscher (64) has calculated this according to an Ångström formula for the eastern Alps in reference to temperature and water vapor relationships at different altitude levels. This has been found to be substantiated by numerous measurements in the village of Lunz. We give here an extract from his results for hot July days (see Table 8).

We learned that outgoing radiation and back radiation were the main factors of the nocturnal heat exchange. Fig. 7 gives a survey

TABLE 8

Altitude (m)	Average Temperature (°C)	Vapor Pressure	Atmospheric Radiation	Effective Outgoing Radiation
3000	1.6	4.6	0.275	0.186
2000	8.6	6.3	0.322	0.189
1500	12.0	7.3	0.348	0.189
1000	14.8	8.5	0.372	0.186
500	17.5	10.4	0.397	0.181
0	21.0	14.3	0.429	0.178

of the entire nocturnal heat exchange in the same manner and the same scale as Fig. 1 for the heat exchange during day time.

The short wave radiation exchange is entirely lacking. The Stefan-

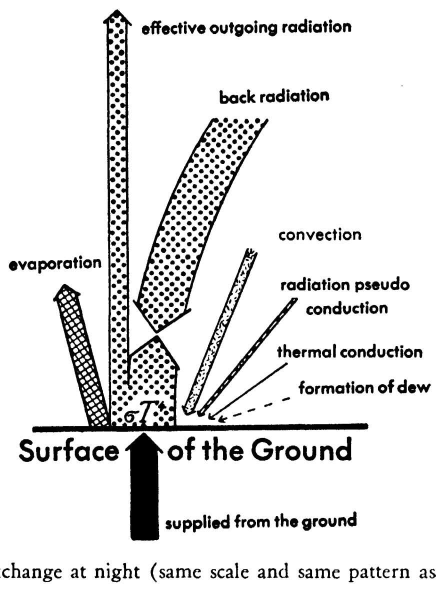

FIG. 7. Heat exchange at night (same scale and same pattern as in Fig. 1)

Boltzmann radiation σT^4 is mostly compensated by the back radiation. The effective outgoing radiation together with the loss of heat by evaporation causes the nocturnal decrease of surface temperature. The width of the arrows representing the effective outgoing radiation in Fig. 7 is a little *smaller* than that of the long wave outgoing radiation (which likewise is considered as the difference between

the Stefan-Boltzmann radiation and the back radiation) in day time in Fig. 1. This fact corresponds with the law, previously mentioned (p. 14), that the outgoing radiation decreases with decreasing temperature. E. Hasché (58) who measured separately the long wave outgoing radiation during day-time established indeed a decrease of the nocturnal values of 7 to 8 percent in comparison with the daytime values.

The temperature decrease of the surface of the ground is diminished by the heat from the deeper layers of the ground which is stored up there during daytime and now is available for the benefit of the surface. As a consequence of the processes (already mentioned with Fig. 1) of heat conduction, convection, and radiative pseudo conduction, the air layer adjacent to the ground also participates in the process of cooling of the surface insofar as it gives up heat to the surface. The respective arrows in Fig. 7 are in opposite direction to those of Fig. 1. As a new fact, the surface profits in heat when dew or frost is condensed upon it; but this gain is negligible except on nights with copious dew.

Also the air itself radiates some heat but according to H. Philipps (*68a*), at the utmost, only a twentieth of the nocturnal fall of temperature can be explained in this way. The cooling of the atmosphere starts essentially only from the ground and we can, consequently, conclude that in the case of the heat exchange by night, the earth's surface plays an important role similar to that of the heat exchange at noon. Just as the boundary surface between earth and air was the seat of highest temperature in the daytime, so does the lowest temperature prevail there at night. The temperature increases thence upward in the adjacent air layer and also downward in the adjacent earth. The vertical temperature distribution at the time when the outward radiation type prevails is therefore a mirror image of that shown in Fig. 2 for the incoming type.

Because a fall of temperature with increase of altitude is the rule, the nocturnal increase of temperature above the ground is called "temperature reversal" or "inversion." It is not limited to the air layer next to the ground, but may extend upward several hundred meters. (See Fig. 20 in Chapter 5.) The amount of the temperature fall, however, decreases very rapidly with the distance from the surface of the earth.

Fig. 8 shows the typical inversion curve for the air closest to the ground, according to the classical investigation of G. Hellmann (59). The values are from measurements taken every 5 cm upward from

the ground and represent the smoothed mean of 14 clear radiation nights.

This study of Hellmann's was the first proof that there is no temperature discontinuity at night within the air layer next to the ground, and that on the contrary the temperature in comparison with the ground continuously decreases, but at an increasingly slower rate. A glance at this diagram makes clear how unfavorable the plant climate is in respect to frost phenomena. We shall deal more fully with this further on.

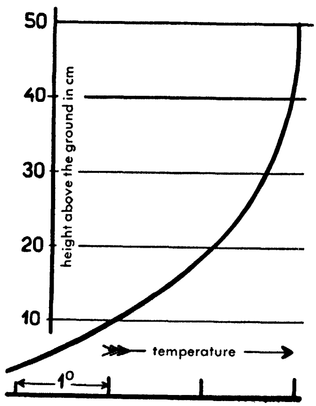

FIG. 8. Nocturnal temperature inversion over the ground. (After G. Hellmann)

There is a temperature discontinuity at the surface of the ground. Within the soil the temperature at first rises very rapidly, then more slowly. Here likewise the outgoing radiation type is the converse of the incoming type. Hellmann, however, did not extend his measurements into the ground.

How it is the solid ground surface which, through its radiation outward, occasions the temperature inversion in the air near the ground, is demonstrated by the following fine observation by S. Petterssen (*68*). On the night of July 30–31, 1927, at 7 P.M., he was making measurements with the Assmann aspiration psychrometer in the neighborhood of Grötöy (68°N). There was no wind. Scattered cirrus clouds were of slight hindrance to the outgoing nocturnal radiation. A thin layer of fog about 3 m thick, lay on the ground and was rapidly thickening, a visible indication of the nocturnal temperature inversion. Above the earth's surface *E* the temperature

distribution was as indicated by the fine broken line in Fig. 9. It is consistent with our outgoing radiation type (Fig. 8). In a ditch 55 cm deep the temperature was only 3.6°C (settling of the coldest air at the lowest point).

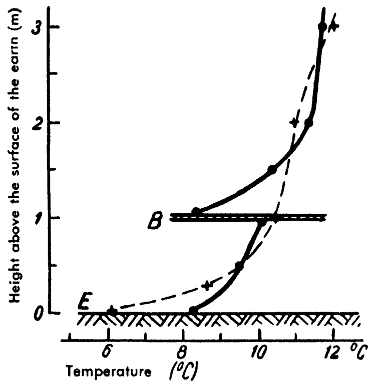

FIG. 9. Double surface produces a double inversion. (Observed by S. Petterssen)

Now in this area there was a barn, to which a wooden bridge, 5 cm thick, led up steeply. While Petterssen was measuring the temperature at various heights, he found, where the bridge *B* lay a meter above the ground, the temperature distribution indicated by the heavy line in Fig. 9. The bridge was acting as a second surface. The air at its upperside was 1.8° colder than the air at its underside. A double inversion had formed, corresponding to the two radiating surfaces, *E* and *B*. The narrow bridge hindered the radiation from *E* directly under the bridge only, so that the temperature there was indeed higher than in the open (broken-line curve) but still the course of the normal inversion, under the influence of the freely radiating surroundings, could be recognized.

CHAPTER 3

True Heat Conduction

The Normal Course of Ground Temperature

In the field of microclimatology there are four different forms of heat transmission: —

1. Conduction (molecular), known also as "physical" heat conduction or "true" heat conduction.
2. Convection, also called "eddy diffusion" or "pseudo-conduction."
3. Radiation.
4. The heat economy of water in its various states.

It has been shown earlier that every body emits radiant heat in accordance with its own temperature (Stefan-Boltzmann law). Radiant heat passes even through airless space, of which the sun furnishes the best example. Just as every body emits radiant heat, so also is it exposed to all kinds of radiation directed toward it from without. The gain or loss of heat through radiation is the resultant of the incoming and outgoing streams.

Conduction and convection of heat require matter. Conduction takes place in all bodies, but convection in liquids and gases only; hence, for meteorology, only in water and air.

According to the kinetic theory of heat, heat energy is conceived of as energy of molecular motion. Lively molecular motion transmits itself to adjacent more sluggish molecules. The faster moving molecules lose energy; the slower ones gain it. In other words, warmer bodies give warmth to the colder ones, with loss of their own heat. This process is molecular, physical, or "true" heat conduction. The bodies, considered as a whole, remain at rest, all their separate parts maintaining their relative position. Thus it is, for example, in the case of an iron rod, heated at one end.

When, on the other hand, there is convection in liquids and gases, the masses themselves are displaced. They retain all their properties; the air, for instance, its content of heat, water vapor and dust. They are brought into contact with ever-varying portions of the liquid or gas. The pseudo-conduction of heat through convection proceeds, therefore, with many hundred times the rapidity of true conduction.

If water evaporates at the surface of the earth there results not

only a change in the moisture content of air and ground, but the energy required to evaporate the water is taken from the surroundings in the form of heat energy. Heat passes off with the water vapor ("cooling by evaporation"). The reverse process takes place when dew is formed. Finally, all precipitation brings from the higher air layers where it originates, its lower or higher temperature, down into the air near the ground, onto the surface itself and finally into the ground, influencing the temperature which it finds there. These phenomena are the fourth mode of heat transmission.

On account of this varied nature of heat transmission, the temperature relationships on both sides of the ground surface are not easily explained. We shall therefore try first to get a clearer understanding of the first three forms of heat transmission. The role of water we shall not consider at present.

We shall begin with true conduction.

Conduction accounts almost exclusively for heat transmission within the earth. Consequently a study of the laws of conduction is the best way to understand ground-temperature relationships. Furthermore, heat processes in the ground govern to a large degree the air temperature near the ground. J. Siegenthaler (*93*) calculated the correlation coefficient between the temperature at 10 cm depth within the ground and the air temperature of the macroclimate as 0.87. How much closer is the relationship with the climate close to the soil!

The speed with which the heat is transferred in the ground, upward and downward respectively, depends upon existing temperature gradients and heat conductivity of the ground. The *heat conductivity* λ is characterized by that amount of heat in cal which flows through a cross section of 1 cm^2 if perpendicularly to this cross section a temperature gradient of 1 °C/cm exists and no heat is conveyed to or removed from any other direction. In the following table (according to R. Geiger (*78a*)) the values of λ are found concerning the most essential substances which are of meteorological interest.

If we assume that only a vertical temperature gradient dt/dx (t = temperature, x = depth of soil) is present in the ground — that there is no horizontal temperature difference, in other words; then the amount of heat W which passes in one second through the square centimeter area is given by the equation

$$W = \lambda \cdot \frac{dt}{dx}$$

TABLE 9

ORDER OF MAGNITUDE OF SOME CONSTANTS REGARDING THERMAL ECONOMY ARRANGED ACCORDING TO THERMAL CONDUCTIVITY

Substance	Thermal conductivity	specific gravity: of the pure substance	specific gravity: of the natural substance (specific volume)	specific heat: per unit of mass of the pure substance	specific heat: per unit of volume of the natural substance	Thermal diffusivity
	(λ)	(ρ)	(ρ_m)	(c)	($C_m\ \rho_m$)	(a)
Dimension:	cal/degr. cm sec	g/cm^3	g/cm^3	cal/g, degree	cal/cm^3, degree	cm^2/sec
silver } for comparison	1.01	10.5	..	0.056	..	1.72
iron } for comparison	0.16	7.8	..	0.11	..	0.19
Granite (rock)	0.011	2.6	2.6	0.2	0.52	0.021
ice	0.0055	0.9	0.9	0.51	0.45	0.012
wet sandy soil	0.004	2.6	1.6	0.3	0.4	0.01
humus	0.003	..	1.3	0.44	0.57	0.005
wet marshy soil	0.002	1.5	0.9	0.8	0.7	0.003
motionless water	0.0015	1.0	1.0	1.0	1.0	0.0015
old snow	0.0007	0.9	0.5 to 0.3	0.51	0.22	0.0032
dry sandy soil	0.0004	2.6	1.4	0.2	0.3	0.0013
oak } for comparison	0.0004 (1)	0.65 (2)	0.69 (3)	0.32	..	0.002 (1)
fir } for comparison	0.0003 (1)	0.49 (2)	0.52 (3)	0.32	..	0.002 (1)
freshly fallen snow	0.0002	0.9	0.2 to 0.03	0.51	0.03	0.0067
peaty soil	0.00015	1.5	0.3	0.44	0.1	0.0015
motionless air	0.00005	0.00129	..	0.24	..	0.161

(1) perpendicular to ligneous fiber — (2) kiln dry — (3) air dried wood

Theoretical physics teaches how the heat cycle which in the course of a day or year arrives at the upper surface of the soil is delayed and weakened as it penetrates within the ground.

The time lag of the maximum and minimum value of the heat cycle is expressed by the following equation. Let x_1 and x_2 be two depths below the ground surface expressed in cm; T, the oscillation period of the heat cycle in seconds ($T = 86{,}400$ for a diurnal heat wave); z_1 and z_2, the corresponding time of reaching the maximum values (in seconds); ρ, the density of the ground and c its specific heat; λ, the heat conductivity as stated above.

Then $$z_2 - z_1 = (x_2 - x_1)\frac{T}{2\pi}\sqrt{\frac{\pi \cdot \rho \cdot c}{T \cdot \lambda}}$$

The weakening of the temperature cycle can be found from the following relation:—If the difference between the highest and lowest value of temperature at depth x_1 equals δ_1, and that at depth x_2 equals δ_2, then

$$\delta_2 = \delta_1 e^{(x_1 - x_2)\sqrt{\frac{\pi \cdot \rho \cdot c}{T \cdot \lambda}}}.$$ The value $a = \dfrac{\lambda}{\rho \cdot c}$

is known as the thermal diffusivity. For the greater is the density ρ and the specific heat c of a body, so much less is the rise of temperature which will be occasioned by a given amount of heat. Many an error has resulted from confusing heat conduction and thermal diffusion. Numerical values for a are also given in Table 9.

In order to represent how this heat movement takes place in the ground, three different methods are used. Either, as in Figures 10 and 14, we show the progress of the heat cycle by lines of equal temperature, using time and soil depth as coordinates; or, we use time as abscissa and temperature as ordinate, as in figures 11 to 13, giving the temperature march at definite depths; or, we choose temperature and soil depth as coordinates and show lines of condition ("tautochrones") at a given time. Fig. 15 is an example of this.

Th. Homén (*82*) the Finnish pioneer in microclimatological observations, carried on a series of measurements at Wakkarais in 1893 dealing with the temperature march at various depths within the soil. They are so valuable even today that we have chosen from them the first example of the variation of soil temperature with time. Fig. 10 represents soil temperature observations in a sand heath at two-hour intervals from Aug. 13, at 6 A.M. to Aug. 14 at

8 A.M. The isotherms penetrating downward toward the right indicate the lag of the diurnal temperature cycle. The lines of small crosses unite the points of highest or lowest temperatures at the various depths. Even at 5 cm below the surface the day's extreme reading is already lagging by two hours; at 20 cm, by five hours. But the extremes are rapidly weakened by depth; the isotherms of maximum and minimum temperatures join not far below the sur-

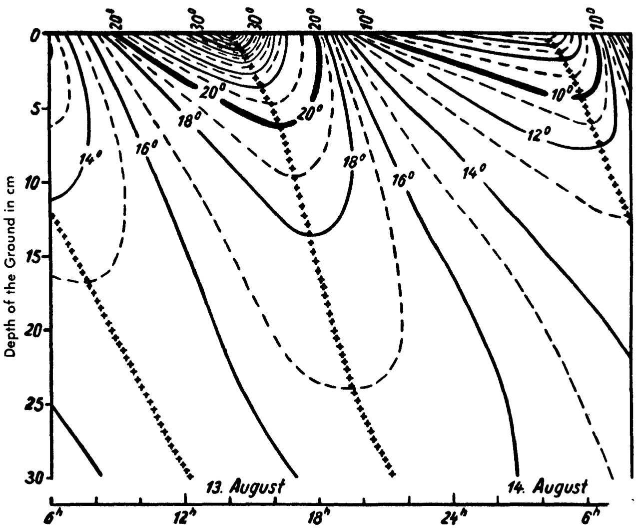

FIG. 10. The very regular penetration of the daily temperature cycle into the ground by heat conduction. (After observations by Th. Homén)

face. Fewer and fewer become the penetrating isotherms; greater and greater the distance between them.

Figs. 11 and 12 show the daily march of soil temperature during certain months, according to observations made at Pawlovsk in 1888 and analyzed by E. Leyst (*85*). They afford a contrast between the month of May, representing a month of the strongest seasonal heating under intensive solar radiation, and the month of January as a winter month with weak radiation.

In May (Fig. 11) the temperature fluctuation is still considerable at a depth of 1 cm below the surface and follows the march of radiation quite closely. At a depth of 20 cm the temperature does not reach its maximum till about sundown. At 40 cm the daily march is reversed, i.e., noon is there the coldest time of day (as an

after effect of night). At 80 cm the daily fluctuation is lacking. That it is spring we know by the cold which is still present in the deeper earth layers (80 and 160 cm).

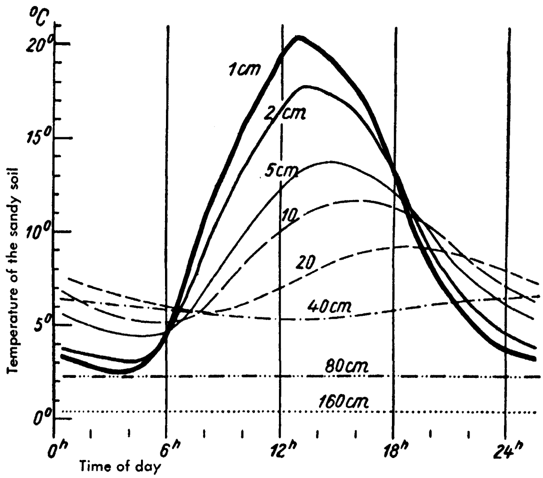

FIG. 11. Daily temperature course in sandy soil at Pawlovsk in May. (After E. Leyst)

In January (Fig. 12) the daily fluctuation is slight at all depths, almost disappearing at 20 cm. But the deeper we go, the warmer the soil—the seasonal antithesis of Fig. 11.

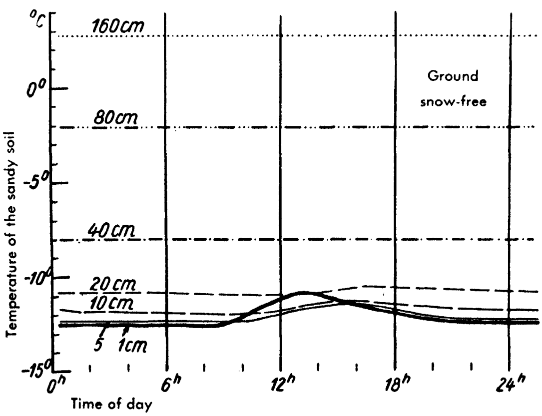

FIG. 12. Daily temperature course in sandy soil at Pawlovsk in January. (After E. Leyst)

Fig. 13, finally, as an example of an annual temperature march, represents measurements made by A. Schmidt (*90*) and E. Leyst (*86*) at Königsberg during the years 1873–1877 and 1879–1886. The extraordinary regularity with which the heat movement in the soil proceeds is so great that the curves appear to have been plotted

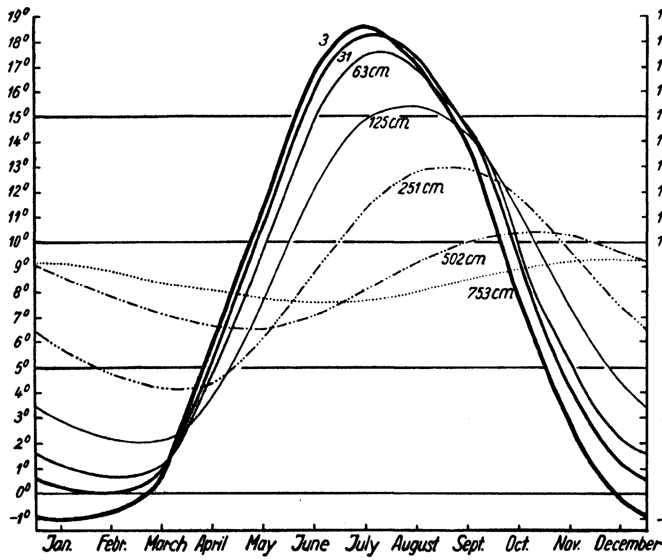

FIG. 13. Annual course of ground temperature at Königsberg. (After A. Schmidt and E. Leyst)

theoretically. The diminution of the annual fluctuation and the lag with depth are evident from one measuring level to the next. At only 7 m below the surface, summer is the coldest season, and winter the warmest! But the difference between the two has there dropped to 1½°.

A person glancing at the course of temperature with reference to time and space as shown in Figs. 11 through 13 may get the impression that it is almost mathematically regular. In reality the temperature march proceeds quite otherwise. The results represented in Figs. 11–13 were obtained on artificially laid-out experimental fields which were kept free from snow during the winter. Under natural conditions the ground is far less homogeneous than on such an experimental field. Not only does its property change with depth but great contrasts can exist side by side. When Wm.

Schmidt (279) had developed a simple method for quickly obtaining ground temperatures under natural conditions, he could detect temperature contrasts within the smallest distances, even in the ground. In addition there is an effect of soil condition, which changes with the weather, variable water content being the most important factor. Winter snow acts as an almost entirely heat-insulating blanket on the earth. An entire chapter, (14), is devoted to the manifold influences of kind and condition of soil.

But even aside from the lack of uniformity in the soil, such mathematically perfect appearing temperature relationships can be obtained only when averaged over a long period of time as in Figs. 11–13 or when quiet days are selected as in Fig. 10 or Fig. 15. Fig. 14

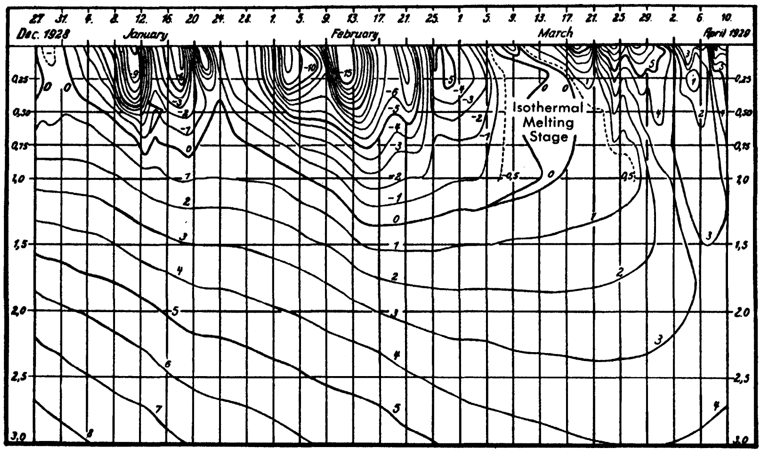

FIG. 14. Ground temperatures under the influence of changeable weather. (Winter 1928/29 at Potsdam)

shows how unsettled the picture of ground temperatures may appear even in an experimental area, when under the influence of changeable weather. It contains the ground temperatures at Potsdam for the winter of 1928–29 according to a sketch by J. Bartels. The scheme of representation is the same as that in Fig. 10. The heat and cold cycles penetrate into the ground from the surface. The depth of penetration depends on the temperature variations at the surface. At the depth of a half meter, weather variations are mostly cancelled out; at depths beyond 1 m the course of the temperature approaches the theoretically anticipated regular form.

In the first two chapters the temperature relationships during the day were designated as the incoming radiation type, while those prevailing at night were called the outgoing radiation type. We can now show, in the case of ground temperatures, how these blend together.

In order to do this we must make use of tautochrones, i.e. lines which show the relation of temperature to depth at a given time. In Fig. 15 this is shown, not for a single instant but for each odd hour of the day, with all the curves assembled for comparison in one diagram. Fig. 15 is made up of measurements by means of thermo-

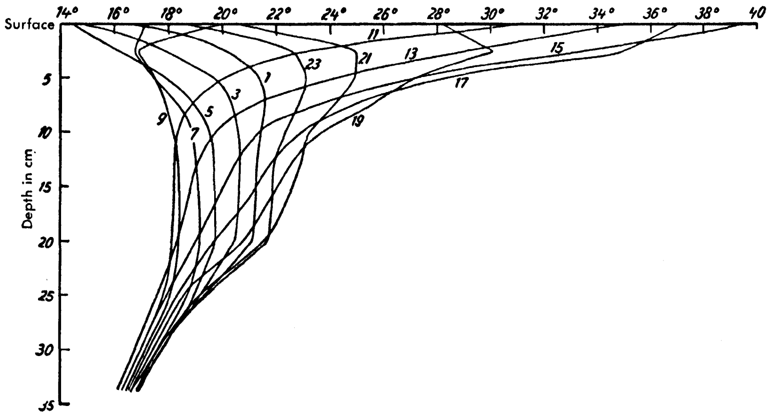

FIG. 15. Tautochrones of the ground temperature on a radiation day in summer. (After L. Herr)

couples, at 10 different depths. They were obtained by L. Herr (*80*) in natural soil near the Geophysical Institute of the University of Leipzig at Oschatz, on the 10th and 11th of July, 1934.

The tautochrone of 3 P.M. corresponds to the incoming radiation type (See Fig. 2, page 7). After 3 P.M. the temperature first falls at the ground surface while in the deeper layers it is still rising. About 7 P.M. the evening cooling is so effective even at 3 cm depth that there the maximum temperature appears as a critical point. The point falls in the course of time to deeper layers and becomes rounded in form. This indicates that the nocturnal radiation outward affects ever deeper ground layers and, down there, loses memory of the day. About 5 A.M., before sunrise the typical outgoing radiation type is attained, the converse of the incoming. And now the

cycle begins again as already depicted save with reverse symptoms.

It must be noted that the lower parts of all the curves in Fig. 15 are closely grouped and inclined upwards toward the right. From this it may be concluded that the day on which the measurements were made happened to be one on which the weather was increasing in warmth.

For the microclimate near the ground, the ground itself acts as a regulating reservoir of heat. At times of heat surplus — at midday, or in the summer — it absorbs great amounts of heat, thus avoiding unduly high temperature and at the same time laying away calories for a time of need. At night, or in the winter it gives up its savings and thus keeps the temperature from falling too far.

The greater the thermal conductivity of the ground, the more effective is its role as a heat reservoir. Microclimates over soils of good conductivity consequently show a smooth march of temperature. On the other hand, microclimates over a poorly conducting soil are extreme — too cold by night, too hot by day. An artificial modification of the soil's heat diffusivity therefore modifies the microclimate near the ground as well. We shall come back to this in a later chapter.

W. Meinardus (*88*) carried out some ground-temperature measurements at Schellal in the extreme desert climate of Egypt during 1914.

In high mountains, with their generally low temperatures, the plant world can thrive only close to the ground. According to J. Maurer (*87*), the amount by which the ground temperature exceeds the air temperature increases with altitude. With the great increase in solar radiation and the slight increase in outward radiation, this is to be expected and would prove that mountain vegetation, even more than that of the plains, is dependent on the climate near the earth. Measurements during the summer months of 1929 and 1930 have been published by W. Hecht (*79*). The one series was made at Korneuburg near Vienna, (167 m msl), and the other at Davos, on the Schatz Alp (1868 m msl). In his work there are to be found some new ideas on ground climate and climate near the ground in mountainous regions. Longer series of systematic measurements are, however, very desirable.

CHAPTER 4

Eddy Diffusion and its Significance

In the foregoing chapter we have dealt with the heat flow resulting from molecular heat conduction downwards from the warm earth's surface into the ground, or upward through the ground toward the cooler surface. A heat exchange of the same sort takes place also between the earth's surface and the air layer adjacent to it. Heat conduction in air is, to be sure, decidedly poorer than in the earth, but air on account of its slight density, does possess good thermal diffusivity. The stream of heat from the ground surface upward (and back), resulting from thermal diffusivity, is equal in its order of magnitude to that flowing downward from that surface.

If we apply this to figures 11, 12 and 13 and imagine "upward" and "downward" there reversed, it follows that the heat of midday would not be felt till evening in the first story of a house, while summer temperatures would not be reached till the beginning of winter. Since this is not true, the heat must be transmitted by some other method. This method is eddy diffusion of heat or, simply, eddy diffusion.

There are two kinds of circulation in water and air: laminar, and turbulent. That circulation is called "laminar," in which there is no whirling motion; if whirls are present, it is "turbulent." Such whirls can be observed in the motion of tobacco smoke in a closed room. In the open where the wind constantly favors mixing, the air is almost without exception in a turbulent state. If the wind is light we do not perceive this turbulence, but if the wind is strong we recognize its gustiness, both as to direction and speed.

Turbulence causes a continuous mixing of air masses. As the masses mingle, so do all their properties. The parcel of air that rises at random from the earth's surface carries with it some heat, a relatively large amount of water vapor, and perhaps dust, radium emanations or what have you. All these properties are transferred into a new location with new suroundings and new conditions. Heat, water vapor, etc., are carried away in the air by this process many hundred times faster than heat is carried by molecular conduction or water vapor by diffusion. Certain kinds of transportation, such as the dispersal of dust, pollen and seeds can be explained in no other way than by this irregular movement.

Alfred Wegener (*114*) has the honor of having pointed out the importance of turbulent movements for meteorology in general. Wilhelm Schmidt's book (*113*), "Eddy Diffusion in the Free Air, and Related Phenomena," which appeared in 1925, was of pioneering significance for microclimatic research problems. H. Lettau (*108*) in 1939 treated the problem of atmospheric turbulence in an entirely new and comprehensive fashion. Anyone with a good mathematical background will find his book very helpful in gaining an acquaintance with the whole problem.

It is the particular purpose of this text-book to present to the reader a clear idea of the eddy diffusion process and what great significance it has for microclimatic questions. To this end we shall derive the fundamental eddy diffusion equations according to Schmidt's simple construction.

Suppose a surface f (Fig. 16) lying horizontally and at rest with respect to its surroundings. If the air as a whole moves forward,

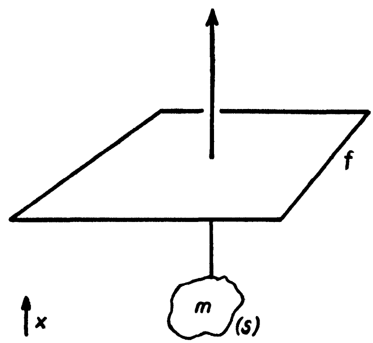

FIG. 16. Diagrammatic representation of the fundamental equation of exchange

the surface moves with it. We shall assume that only eddy diffusion is active. Let the air have the property s per unit of mass — leaving open what this property is. The only requirement is that it must be free from outside restrictions. The property s can therefore be the content of dust, heat or water vapor, and is generally a function of altitude.

Suppose that, in consequence of eddy diffusion, the mass m passes upward through the surface f; it thereby carries with it the quantity $m \cdot s$ of the property. All the particles of air from below which, by eddy diffusion, pass through f bring $\Sigma m_{+} \cdot s$ with them, if we consider the direction upwards as positive. In a corresponding manner

all the air particles from above bring $\Sigma m_{-} \cdot s$ with them. There passes upward through the surface f therefore, in the very small time which we are considering, only the difference between the properties moving upward and those moving downwards. This flux is $\Sigma m_{+} \cdot s - \Sigma m_{-} \cdot s$. If we refer this flux to unit surface and unit time (t = time in seconds) and if the flux is designated by $\mathfrak{S}$, then $\mathfrak{S} = \frac{1}{f \cdot t} [\Sigma m_{+} \cdot s - \Sigma m_{-} \cdot s]$. We assume moreover that the property is arranged above the ground at a height x_1 (in cm) precisely according to a parobola. According to experience the change of all factors in the climate near the ground which increase with altitude, can be expressed by a parabola. If s_0 be the property at the height $x = 0$, then

$$s = s_0 + \frac{ds}{dx} \cdot x + \frac{1}{2} \frac{d^2 s}{dx^2} \cdot x^2$$

If we substitute this in the above-given equation, we get —

$$\mathfrak{S} = \frac{1}{f \cdot t} \left\{ s_0 \left[\Sigma m_{+} - \Sigma m_{-} \right] + \frac{ds}{dx} \left[\Sigma m_{+} x - \Sigma m_{-} x \right] - \frac{1}{2} \frac{d^2 s}{dx^2} \left[\Sigma m_{+} x^2 - \Sigma m_{-} x^2 \right] \right\}$$

The first expression in brackets [] is equal to zero because, according to premise, no mass stratification takes place through eddy diffusion, and just as great a mass passes downward as upwards. We shall further assume that eddy diffusion proceeds symmetrically with respect to surface f. For each mass at the distance $x = +q$ there will be found an equally large mass which comes to f from the distance $x = -q$. The last expression in brackets also becomes zero and the equation is simplified into

$$\mathfrak{S} = \frac{\Sigma m_{+} x - \Sigma m_{-} x}{f \cdot t} \cdot \frac{ds}{dx}$$

The factor which precedes $\frac{ds}{dx}$, adds nothing more to the property s of the moving airmasses but only indicates the liveliness of the motion. If we call this A, then

$$\mathfrak{S} = A \cdot \frac{ds}{dx}$$

Comparing this short formula with the one on page 27 we recognize eddy diffusion as a heat conduction having the value A in place of the constant λ. This has led to eddy diffusion of mass being called also "pseudo conduction."

Now while λ is a physical constant, which depends entirely on the material under consideration, A changes with time and place. A is called the austausch coefficient: its value varies (if the c-g-s terminology is used) from 0.001 to 100 — within wide limits, in short. It is the simplest expression to designate the condition of irregular motion in the air. The dimension of the coefficient is $cm^{-1} \cdot g \cdot sec^{-1}$.

In the preceding derivation two assumptions were made. In the first place the property s must be independent of outside conditions. In general, therefore, temperature cannot be used as such a property, since it depends on pressure. For the air layer near the ground this limitation vanishes, since the vertical extent is so little that thermodynamic temperature changes may be neglected.

In the second place it was tacitly assumed that eddy diffusion was operating alone. In reality, however, the processes of molecular physics (conduction and diffusion) cannot be eliminated. For the most part these are quite unimportant in action compared with eddy diffusion as the considerations at the beginning of this chapter make clear. The effect of eddy diffusion is 10 to 100,000 times as great as that of heat conduction. Just at the ground surface, however, this assumption may not hold, which is something for microclimatology to consider. Even the supposed symmetry of eddy diffusion does not always exist close to the ground. Furthermore there is in the climate near the ground a second kind of pseudo-conduction through radiation, of which we shall treat in the following chapter. This too warns us to be cautious in the use of the eddy diffusion equation.

In spite of these limitations the important fact remains: Although within the ground heat is largely transported by conduction, yet in the air near the ground, it is predominantly eddy diffusion which both by day and night moves the heat upward from the earth's surface, and vice versa.

First we shall look at some figures on the magnitude of the austausch coefficient A. W. Schmidt (*113*) has computed its value according to very different criteria. The following extract from his compilation shows not only probable values of A, but also the great number of ways it can be calculated, as well as the general significance of eddy diffusion. He found: —

(1) from the distribution of smoke streamers above a field where there was particularly stable stratification about sunrise, $A = 0.006$;

(2) from the heat transfer over a snow cover on a clear, calm winter night, according to A. Ångström's measurements at Abisko, $A = 0.14$;

(3) from the daily temperature march at Paris (15 year average) in the layer between 2 m and 123 m above the ground, $A = 9$;

(4) from the scattering of the pollen from our forest trees over the Baltic, $A = 43$;

(5) from the distribution of wind velocity and direction at different heights at the Eifel tower, $A = 90$.

More recent measurements substantiate the accuracy of these figures.

The coefficient A increases with height above the ground. This increase, as H. Lettau (*108*) has shown, follows theoretically as well as according to actual measurements. At the ground, therefore, eddy diffusion as well as wind velocity is subject to a braking effect. (See Chapter 11.) At the same time, as W. Haude (*132*) has cogently remarked, larger units of turbulence are "ground up" at the ground into smaller and smaller ones.

The linear increase of A with altitude is however only a theoretical law which has decided variations near the ground in individual instances. It has often been observed that eddy diffusion varies unevenly from one layer to the next. Thus H. Berg (*98*), in his measurements on the Bissendorf moor near Hanover in 1934, proved that within the first meter above the ground A increased slowly, then rapidly up to 5 m, but from there up to 16 m was almost constant. W. Haude (*132*) made some observations over an area of broken stone in the Gobi desert, on March 7, 1932, at 2:15 P.M. Next to the ground was a layer 25 cm thick, showing weak eddy diffusion. Above this A increased quickly to many times its lower value. But between 70 and 80 cm there was again a much slower increase.

From all this we may conclude that the air layer adjacent to the ground has a laminar structure. This is suggested by other circumstances as well, and explains many phenomena otherwise hard to understand. One hot summer day I noticed, on the Peiting moor in upper Bavaria, that if the eye was placed about a meter above the ground a sharp boundary layer could be seen, below which the air showed irregular streakiness, and above which there were threadlike streaks like smoke waving in the wind. When taking temperature measurements during the day one often observes within the basal air layer a secondary temperature rise at some height, say 1½ m,

above the ground. It is the so-called "secondary temperature maximum" which was discovered by Hornberger (*106*) and described by P. Vujevic (*197*) but was attributed to observational errors. R. Geiger (*179, 180*) confirmed it repeatedly even in monthly means, as can be seen in the following 8-hour observations at the Anzinger Sauschütte near Munich.

A. Schmauss (*111*) referring to the "rising current of air," which is often mentioned in meteorological theory but hard to find in nature, mentions the research of R. E. Liesegang. He poured into a beaker 200 g of very fine-grained powder of Caffeine-sodium salicylate with 400 cc of cold water. After agitating a short time, the beaker was placed in a hot-water bath and allowed to remain there undisturbed. When, some 10 minutes later, the powder had dissolved, the liquid showed horizontal stratification into 8 or 10 layers. The decreasing concentration upward was not continuous, but by steps. The sharp boundaries between the several strata could be easily recognized through the varying light refraction. To produce the phenomenon it was necessary to warm the solution from below. A similar stratification was evident in other solutions of salts and colloids. These processes may be considered analogous to the formation of a foliated structure in the dust-filled air near the ground when it is warmed from below at midday. The secondary temperature maximum would indicate a limiting layer which through local conditions can have a preferred position and therefore can be found regularly at a certain height.

TABLE 10

Month, 1924	Mean Temperature (Six's thermometers)			
	0.05	0.50	1.00	1.50 m
May	15.09	14.05	14.23	13.85 °C
June	16.41	15.45	15.60	15.19 °C
July	18.48	17.41	17.45	16.88 °C

Eddy diffusion has two causes which, as early as 1919 were differentiated by A. Ångström (97). *Dynamic* eddy diffusion is caused by the turbulent streaming of the air. According to H. Lettau (*108*) the austausch coefficient *A* increases linearly with the wind velocity: at any rate, this rule is valid for the wind regimes of that portion of the air layer near the ground. The *thermal exchange* is added which originates from the instability of the thermal stratification. This

explains the above mentioned fact that the exchange coefficient is dependent also upon the stratification of temperature in the air near the ground.

One remarkable observational fact remains that the computation of A on the basis of the variation of wind speed with height does not show such a dependency on the respective temperature stratification. Since this is the same process of exchange which causes momentum and heat transfer (water vapor, etc.), this result is surprising. With different methods different values of A result. As an example, H. Lettau (*107*) calculated from simultaneous observations at the geophysical observatory of Leipzig that $A = 20.0$, if temperature measurements are taken into consideration; $A = 2.8$ if the wind measurements are taken.

To explain this seeming contradiction, one may point to the before mentioned factors neglected during the derivation of the exchange equations: there is especially the neglect of the radiation phenomena which certainly are of importance for the heat process but not immediately for air motion. F. Albrecht (*96b*) recently gave us an explanation. He assumes that within the air current aloft large turbulence bodies (order of magnitude: 100 m diameter) exist; these may descend vertically and be broken up to smallest turbulence bodies near the ground. Such a concept of the turbulence near the ground can agree with the fact that momentum on the one hand, heat and water vapor on the other, are exchanged between air and ground in different ways. It also puts the outstanding importance of the dynamic exchange, which exists beyond all doubt, in the right place.

In conclusion let us look at a few examples of how the action of eddy diffusion of mass becomes visible directly or otherwise. (The optical side will be treated only in Chapter 12.)

A. Büdel (*100*, *101*) followed the life history of individual turbulence units which he made visible by means of smoke and whose course he observed through motion pictures. He also produced a vertical smoke band by means of a smoke pot falling from a height of 40 m and measured its drift and dispersion.

Even earlier W. Schmidt (*112*) had used movies in the study of eddy diffusion. He allowed light wire frames connected by half transparent material, such as a bridal veil, to follow irregular wind movements, recording their position in moving pictures taken as rapidly as possible. Fig. 139 in Chapter 28 shows an example of his

measurements. We can see there the limitation which the influence of the ground imposes on the diffusive process.

Fig. 17 deals with the effect of the weather. In it eddy diffusion is recognizable in the irregular temperature fluctuations which R. Geiger (*102*) observed thermoelectrically on the Main meadows

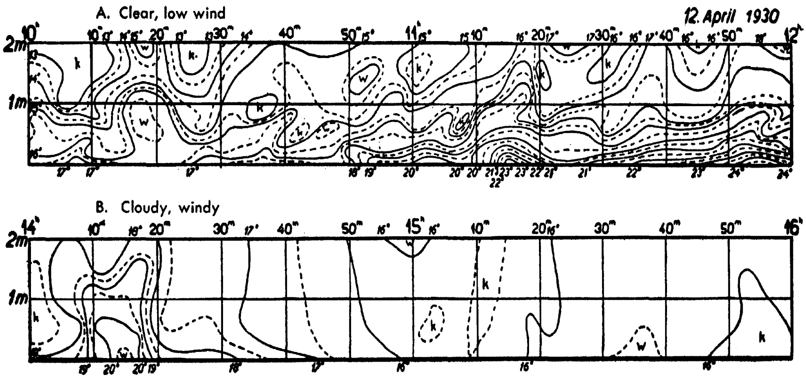

FIG. 17. Temperature unrest in relation to weather. (After R. Geiger)

at Schweinfurt in April, 1930. The upper strip is the record of a calm, sunny day. Between 10 and 12 in the forenoon it can be plainly seen by the isotherms (1° solid lines, ½° broken lines) that incoming radiation prevails. At times, however, the temperature fluctuates

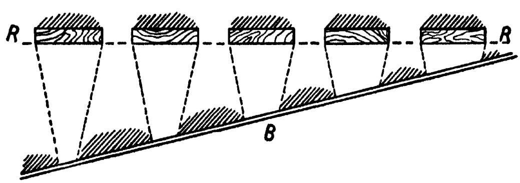

FIG. 18. Eddy diffusion of mass made visible. (Observed by A. Schmauss on January 8, 1931 and January 26, 1937)

rapidly. The superheated layer next to the ground at times clings closely to the surface, at other times it separates from it. Small masses of warm air ascend (10:52), cold air descends (11:01).

In contrast to this is the lower half of Fig. 17. The cloudy day brought little heat radiation to the ground, with consequently slight heating of the adjacent air layer. The wind increased eddy diffusion so that temperature gradients which did form near the ground

were quickly obliterated. Lively eddy diffusion and weather unfavorable to radiation account, therefore, for the quiet aspect.

At the Munich Meteorological Institute, I was called to the window one day by A. Schmauss, who directed my attention to the following phenomenon on the other side of the courtyard. (See Fig. 18): Above the gently sloping tin roof *B* of a wash-house there was fastened a grating *R* which formed the floor of a drying place on the roof. When there was a light snowfall with little wind (as on Jan. 8, 1931 and Jan. 26, 1937) the grating appeared white-banded with narrower black intervals, while the roof beneath appeared likewise, *not* black-banded with narrower white strips of snow. The short distance of a few decimeters which the snow had to fall between grating and roof sufficed to broaden by eddy diffusion the snow band falling through the narrow spaces of the grating. Only when *R* and *B* closely approached one another as at the right in Fig. 18, was the fall so little and perhaps eddy diffusion so much weakened, that black strips with narrower bands of snow between were seen on the tin roof.

F. Rossmann (*110*) makes a very original contribution in his essay on "Circulation in the Matchbox."

The importance of eddy diffusion can be shown, finally, in the dispersal of pollen and seeds. Assuming a laminar wind movement, even spores, with their very slow rate of settling, would not get very far. In no case could they rise higher than their source in the plants which bore them. Mass convection, however, with its irregular movements, scatters these particles widely. They find themselves now in rising, now in falling, airmasses unpredictably. Part therefore reach the ground sooner; part considerably later. To observe light, winged seeds in their flight is one of the most interesting studies of eddy diffusion which nature gives us an opportunity to make. The lower the rate of settling and the greater the eddy diffusion, the wider is the distribution. W. Schmidt (*113*) who grappled with this problem mathematically was able to show that with decrease of settling speed the distances the particles were carried increased with extraordinary rapidity. If, by average limit of dispersal, we understand that distance to which at least one percent of the scattered seeds attain, and if we use an austausch coefficient of $A = 20$ and a wind velocity of 6 m per second, the following dispersal limits shown in Table 11 result.

The light spores of the lycoperdon are therefore unquestionably scattered over the whole earth. Observations on land, on sea and along the shore have confirmed these theoretical results. H. Rempe

TABLE 11

Substance	Sinking Rate cm/sec	Average Dispersal Limits in km
Fruit of the ash (Fraxinus excelsior)	200	0.03
" " " fir (Abies pectinata)	106	0.09
" " " pine (Picea excelsa)	57	0.3
" " " birch (Betula verrucosa)	25	1.6
" " " dandelion (Taraxacum officinale)	10	10
Pollen of spruce fir (Pinus silvestris)	5.3	40
Spores of clubmoss (Lykopodium)	1.76	330
" " " (Polytrichum)	0.23	19000
" " " (Lycoperdon)	0.047	460000

(*109*) has published a more recent study of this question. The forester in scattering finely-divided poisonous powders from airplanes over forest nurseries in the war against insect pests, is making practical use of the law of mass eddy diffusion. R. Geiger (*103*) has published meteorological experiences in this field.

CHAPTER 5

Long Wave Radiation

The heat exchange between ground and air and the heat exchange within the air layer near the ground is caused not only by heat conduction (see Chapter 3) and convection (see Chapter 4) but also by the exchange of heat in consequence of the long wave heat radiation of the surface and the air itself.

Since 1931, G. Falckenberg (*117*) hinted at the fact that the depth of the long wave radiation in the air is so small that the absorption by air should not be neglected if the thermal economy of the air layer adjacent to the ground is considered. There can be no doubt about this kind of radiation exchange; but as far as its importance is concerned for the entire thermal economy, there exist very different opinions nowadays.

Generally, the long wave radiation exchange is reckoned into the effects of convection, and that because the observations, for example, of temperature stratification do not permit the separation of both influences. That means that the radiation is considered as an unessential additional part of the exchange. G. Falckenberg, however, and his followers consider the nocturnal cooling of the ground as caused essentially by such radiation processes. In this chapter we will get better acquainted with his idea.

From Chapter 2 (page 13) we have learned that the greatest intensity of radiation from ground and air according to the low temperature (in comparison with the sun) lies within the long wave portion of the spectrum. From Wien's law we calculate:

for a temperature of:	−40	−20	0	+20	+40°C
the wave length of maximum radiation intensity	12.4	11.4	10.5	9.8	9.2 μ

The absorption of the long wage radiation emitted from the ground during day and night is caused (as has already been briefly mentioned in Chapter 2, p. 13) primarily by water vapor and carbon dioxide of the air. Fig. 19 shows the absorption spectrum of the two gases according to F. Schnaidt (*127*). In the upper portion (of the figure) the absorption coefficient of water vapor, equivalent to 0.01 cm of precipitable water is represented as dependent upon the wave

length λ. The visible portion of the spectrum (0.4 – 0.8 μ) lies on the left side beyond the figure. In this most effective portion of the solar radiation the absorption of water vapor is negligible. The first absorption band is at 3, another, more effective, is between 5 and 9 μ

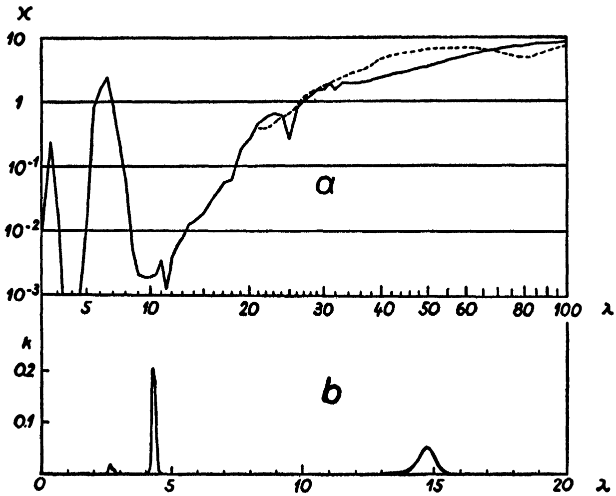

FIG. 19. Absorption spectrum for (*a*) water vapor and (*b*) carbonic acid. (After F. Schnaidt)

with the maximum at 6.3 μ. Beyond a comparatively diathermic portion the absorption increases, starting from 12 μ, rapidly and continues remaining high. Carbon dioxide, whose absorption coefficient is represented in the lower portion of Fig. 19 (but in another scale regarding wave length), shows two bands with sharp boundaries, at 4.3 and 14.7 μ. The comparison of the absorption spectrums with the array of numbers shown above for the wave length of the strongest outgoing radiation shows that these fall in the region of rapidly increasing absorption. The absorbed part of the radiation hence varies with the temperature of the radiating surface.

The relationship between the emissivity of a body and its absorptivity is constant at a given wave length and temperature, according to Kirchhoff's law, and the air is thus a "band radiator," since it absorbs in bands. It is thus different from solid ground, for the latter is, in the region of long wave lengths, practically a "black body"; as will be shown in Chapter 13 (see page 130), it absorbs all radiation falling upon it. It is thus also a "black body

radiator," that is to say it emits at all wave lengths indifferently.

This difference between the black body radiation of the ground and the band radiation of the air leads to the phenomenon which G. Falckenberg (*116*, *118*) has called the *wave length transformation*. When for instance the earth's surface is cooled by outgoing radiation at night, heat is returned to it by the warm air next to the ground in the form of band radiation. The ground surface which receives this energy transforms it into radiation with a practically continuous spectrum as it leaves the solid earth which is in effect a "black body." This radiation emitted by the ground meets a two-fold fate. As much of it as falls within that part of the continuous spectrum belonging to the water vapor and carbon dioxide cannot get out. It is absorbed. Part of this energy is given to the higher air layers and passes away into space. Another part gets back to the earth.

Those wavelengths, however, which do not belong to the bands mentioned, pass through the air unhindered. Their energy is "effectively" radiated. The ground consequently is cooled, but only the lowest air-layer is cooled, for it can now return energy through band radiation to the once more cooler ground. This, in turn, gives back only a part as utilizable to the air, while it loses a part for good as a result of wavelength transformation, and itself cools off still more.

According to G. Falckenberg (*118*) and F. Schnaidt (*127*) the depth of the long wave radiation is very small. It is only a few meters and for some wave lengths even less than 85 cm.! The air layers at a somewhat greater distance from the ground do not cool immediately by radiation towards the cold ground, but by radiating towards the lower air layers, which, on their own part, are already cooled by radiation. Therefore, the cooling process is propagated very slowly upwards. Hence, E. Stoecker speaks of a *radiative pseudo conduction*; as with the genuine heat conduction, in consequence of the short path of the molecules, the heat is conducted only slowly, also with radiative pseudo conduction heat is transferred slowly in consequence of the small range of the long waves.

The followers of Falckenberg pleaded in favor of the opinion that the slow rise of the inversion layer in the evening (see p. 49) is caused chiefly by these radiation processes. Nevertheless, the theory of H. Philipps (*68a*) which considers simultaneously mass exchange *and* radiation permits calculation of this lifting of the inversion in the evening in full agreement with the observations. Be that as it may, G. Falckenberg's observations at the aerological observatory of

Rostock offer excellent examples of the nocturnal development of inversions. By means of Fig. 20 we give results of observations taken from a paper of O. Steiner (*130*).

The evening of July 20th, 1925, was cloudless with wind from east and south (from inland). About 6 P.M. a decided fall in temperature set in at the ground (heavy line) more than two hours before

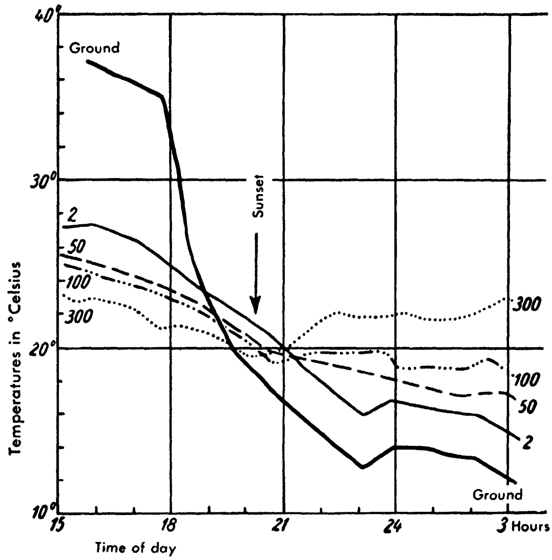

FIG. 20. Formation of the nocturnal temperature inversion in the lowest 300 m. on July 20, 1925 at Rostock. (After O. Steiner)

sundown, for by this time the balance was already in favor of outgoing radiation. (How often we observe, while out walking on an autumn evening that the ground is already stiffening with frost although to sight and touch the air seems warmer!) The temperature fall continued, slowing up somewhat as the sun went down, until about midnight. In comparison with the course of the ground temperature, Fig. 20 shows the course at heights of 2, 50, 100 and 300 m above the earth. The evening decrease of temperature becomes less, the farther the air is from the earth's surface. The various degrees of cooling result, about the time of sunset, in an equality of temperature throughout all layers (isothermy) and, a few hours later, in an inversion. At 300 m above the ground the course of the temperature has, consequently, more the appearance of accidental

variation than of a regular daily cycle. The effect of radiative pseudo-conduction scarcely reaches that high.

The effect of wave length transformation extends, it must be concluded, to the daytime, likewise. Solar radiation causes a rise of the temperature of the earth's surface; this temperature rise leads to an increase of ground radiation, which occurs as an almost continuous spectrum. A part of this ground radiation is taken in by the absorbing bands of the air and this part causes a slowly moving heat wave to rise from the ground, which is therefore attributable to radiative pseudo-conduction. The portion of the ground radiation not absorbed in the air is lost to the earth.

The question what share of the heat transport in the air layer near the ground should be given to the mass exchange and what to the radiative pseudo-conduction cannot yet be decided. Recently B. H. Ch. Brunner (*115a*) estimated mathematically the share of radiation on a summer day as, at the highest, 5 percent. In any case, the arrows in Fig. 1 (page 3) and in Fig. 7 (p. 22) marked as long wave radiation and which represent the quantitative influence of the radiative pseudo-conduction are rather too large than too small.

SECTION II

TEMPERATURE RELATIONSHIPS NEAR THE GROUND

CHAPTER 6

The Warming Process

In the earlier considerations of the incoming and outgoing types of radiation attention was drawn to the great significance of the earth's surface to the general heat economy, by day as well as by night. It was further indicated what temperature conditions are to be found in both extreme cases. In Chapters 3 through 5 it was then explained how the movement of heat proceeds within the air layer adjacent to the ground and in the ground itself. Let us now turn our attention again to the two radiation types and endeavor to understand the mechanisms of the heating and the cooling processes.

The movement of heat at midday from the heated ground downwards into the deeper earth layers appeared fairly simple. Here true conduction ruled almost alone. In Chapter 3, therefore, we could deal with temperature relationships within the ground.

At midday also it is true conduction which causes the flow of heat from the heated ground to the air molecules adjacent to it. It is appropriate to designate as the "boundary layer" that thin skin of air above the ground surface in which heat movement proceeds chiefly through molecular heat conduction. It will have a thickness of a few millimeters at most, and on winter nights according to recent measurements of A. Nyberg (*345*), even less than 1 mm. We shall imagine its upper limit located at the place where the heat transfer by eddy diffusion equals that resulting from true conduction. The discussion in Chapter 5 shows that in addition to these two effects there is also some transfer of heat by radiation in this boundary layer.

The agricultural meteorologists of the Indian school, under the leadership of L. A. Ramdas have recently been working successfully from both the theoretical and the practical angle on the subject of heat transmission from the heated ground surface into this boundary layer. There are great technical difficulties in measuring the temperature distribution close to a surface. L. A. Ramdas and M. K. Paranjpe (*138*) have succeeded in determining it optically, through interference within the first millimeters above a surface without dis-

turbing the natural layering by means of the measuring equipment. Above an electrically heated plate, in a room temperature of 22.5°C they obtained the following values:—

TABLE 12

Distance from the heated surface in millimeters:												
0.0	0.025	0.05	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0.
Temperature in °C:												
87.58	82.0	79.6	77.4	74.0	71.2	68.8	66.6	64.4	62.0	60.0	58.0	56.5.

There is therefore a temperature jump of 10°C in the first tenth of a millimeter! With such a temperature gradient a strange phenomenon takes place. In dust-filled air the separate dust particles next to the hot surface receive stronger blows from the more lively moving molecules on the side with the higher temperature. They are therefore subject to an excess of pressure from that side and move away from the heated surface. This results in the formation of a very thin, dustfree boundary strip which in certain light shows up dark in contrast with the dust-filled air above it, which reflects the light. This dark strip affords proof of how heating proceeds with increasing distance from the ground.

According to the observations of L. A. Ramdas and S. L. Malurkar (*137*) the upper surface of the dark strip is in continuous wave-like motion. We shall return to this subject in connection with optical phenomena. (See Fig. 60.) In several places the superheated air now begins to lift the boundary layer in tongue-like forms.

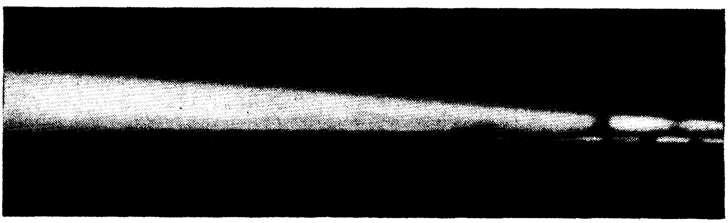

FIG. 21. The beginning of the upward eddies in the boundary layers next to the ground. (After experiments by L. A. Ramdas and S. L. Malurkar, 1932)

Fig. 21 is a photograph by the author which shows this. The heated plate, visible below as a bright strip, is overlain by a cloud of brightly lighted, artificial dust. The dustfree layer, which appears

as a narrow dark interval, is, in several places, extended upward in the form of tongues. It is in these places that the superheated air is breaking through upward. Here is where eddy diffusion begins.

These experiments have been with entirely uniform surfaces, such as do not exist in nature. Such surfaces are, however, necessary for a thorough understanding of the heating process because they show how, even under these unfavorable conditions, the transition from pure heat conduction to convection takes place.

Now we take a further step. From the "*boundary* layer near the ground" we pass to the "*intermediate* layer near the ground."

On rough and stony ground in the desert of Gobi, W. Haude (*132*) undertook measurements of the temperature close to the ground surface. Fig. 22 shows in the upper part the course of the temperature at 1 mm (solid line) and at 1 cm (dotted line) above the ground. The Albrecht platinum wire thermometer which he used was very suitable for the distance from the surface. The registration was rapid, Fig. 22 covering only 4½ minutes at about noon on Feb. 28, 1931. In the lower part of the figure is an isoplethic representation of the vertical airlayer between the 1 mm and 1 cm levels.

Even at only 1 mm above the ground there is considerable temperature disturbance — a symptom of eddy diffusion. We must remember that the platinum wire used in the measurement was between 8 and 10 cm long. Consequently it independently integrated all the inequalities within this horizontal distance. A measuring *point* would show a considerably livelier state of unrest. In any case it can safely be concluded from the observations that the point of measurement at 1 mm above the ground is already above the boundary layer.

But we have still not reached the layer where eddy diffusion is fully effective. In order to save space, the 3° line in Fig. 22 is superimposed on the 6° line. There is actually quite a distance between the solid and the dotted lines. This indicates that with all the disturbance of the temperature at both places, which are only 9 mm apart, there is nevertheless no exchange of air between the two layers. At a height of 1 mm it is much warmer than at 10 mm. With all the ups and downs of temperature the lowest point of the fluctuating temperature at 1 mm still does not approach the highest temperature at 1 cm.

Above the boundary layer, then, there is a region within which there is already vigorous eddy diffusion taking place under the influence of the strong temperature gradient. Still, its vertical effectiveness

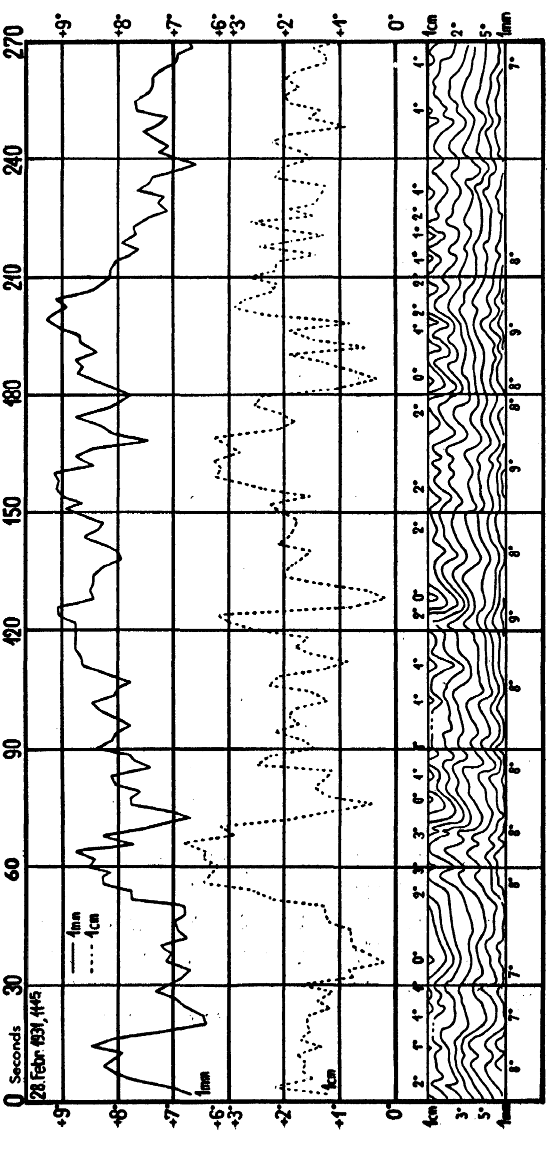

FIG. 22. Temperature recordings over desert land. (After measurements by W. Haude in the Gobi Desert, 1931)

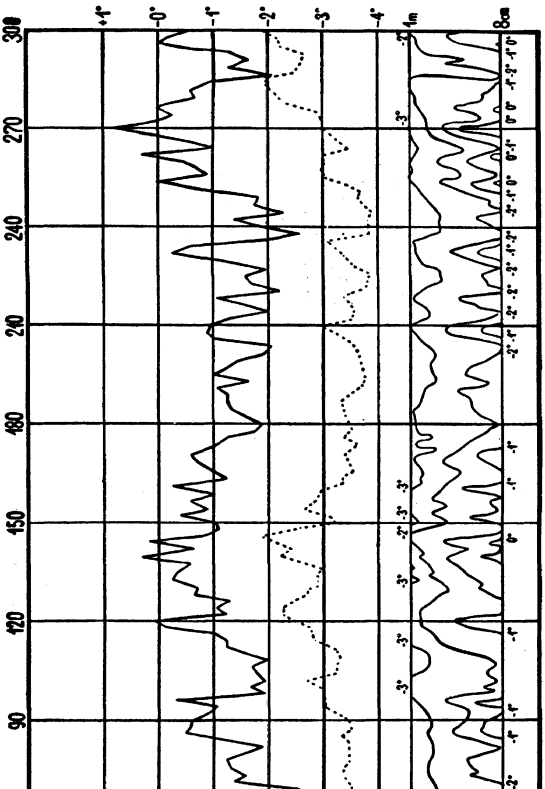

FIG. 23. Temperature recordings of the "over layer" near the ground in the Gobi Desert

is restricted by the damping action of the adjacent ground surface. It is this layer which we call the "intermediate layer" near the ground.

Above this, in turn, is a third layer, which, to distinguish, we shall call the "overlayer" near the ground. This is where vertical eddy diffusion comes into full play as compared with the intermediate layer lying beneath it. The overlayer includes the greater part of

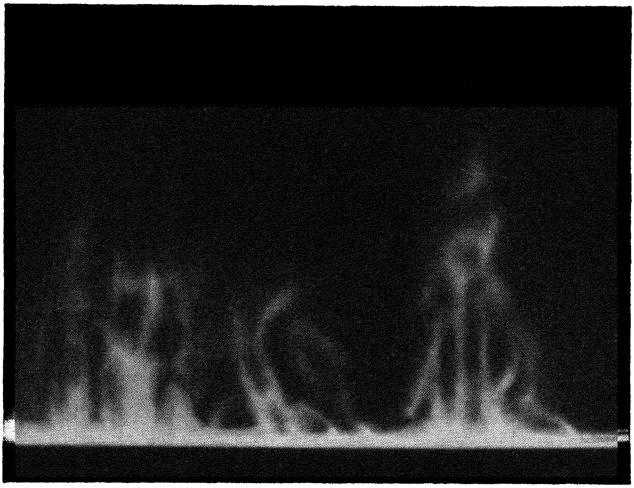

FIG. 24. Upward eddies of hot air, made visible by water vapor. (Photo by L. A. Ramdas and S. L. Malurkar)

the whole air layer near the ground. In contrast, however, with the province of the macroclimate which lies next above the overlayer, the urgency of heating from below is here still so great that, in spite of lively eddy diffusion, it is possible to maintain a vertical temperature gradient of considerably more than 1° per 100 m during the period that incoming radiation prevails.

To take an instance from the region of the overlayer, we shall again use the measurements of W. Haude (*132*) in the Gobi desert. Fig. 23 shows a record made with the same apparatus and on the same day as that in Fig. 22, but 17 minutes later. The measuring points are now located 8 cm and 100 cm above the ground. The vertical distance between the two points of measurement is a hundred times that in Fig. 22. Nevertheless the lower temperatures at 8 cm are equivalent to the high temperatures at 1 m. From this we

may conclude at least that air parcels move back and forth between the two places of measurement.

Fig. 24 is intended to illustrate the strong vertical mixing in the overlayer. It is taken from the work of L. A. Ramdas and S. L. Malurkar (*137*). Upward streaming of the warm air is rendered visible by some water which was placed on the hot surface. It takes place irregularly, according to the nature of eddy diffusion. In certain places the heated air breaks through upwards. In the darker places the necessary compensating downward movement of cold air takes place. From the processes shown in Fig. 24 up to water spouts and dust whirls, is only a difference in magnitude — not in kind.

We already called attention in connection with Fig. 17 to the extraordinarily unsettled condition of the temperature as a special characteristic of the whole climate province near the ground. Fig. 25

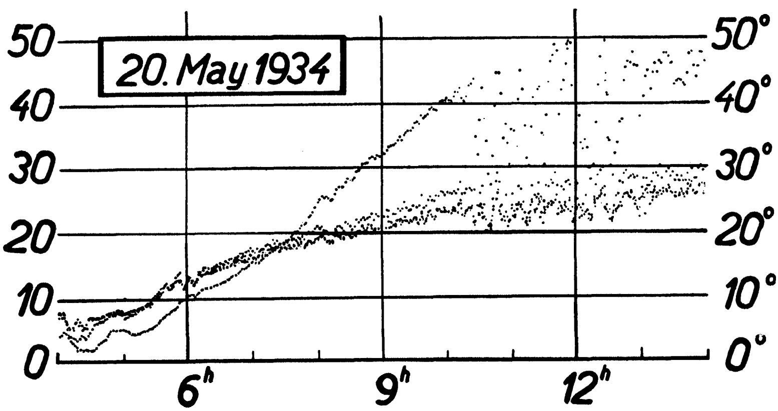

Fig. 25. The large temperature unrest after 10 o'clock (incoming-radiation type) is characteristic of climate near the ground. (Recorded by R. Geiger in Munich)

will make clear how temperature conditions during the period of incoming radiation contribute to the development of such a condition. It covers a record made with engraved stem thermometers by R. Geiger (*131*) by means of a Hartmann and Braun recorder located at heights of 0.23 cm, 100 cm, and 200 cm above the ground at the Munich airport. At 0 cm the thermometer lay on the ground, which was covered with a short, dry sod.

At the beginning of the record the curves are so placed that the highest temperature corresponds to the highest point of the curve (Inversion, outgoing radiation type). In the overlayer from 23 to

200 cm the transition to incoming radiation type takes place between 5 and 6 o'clock; the curves intersect. From then on, the upper curve corresponds to the 23 cm height. In the air layer next to the ground, which is confined by the blades of grass, it remains relatively cold. Not until after 7 o'clock does this layer share equally in the warming up process, after which time it proceeds rapidly.

When, after 10 A.M. the incoming type of radiation, with its steep temperature gradients, comes into full play, it seems as though the temperature curves are suddenly destroyed. Vigorous eddy diffusion scatters the readings over a wide range. If a person wanted to find the average temperature for the time between 12 and 1 P.M. at a certain height, it could be only a theoretical figure. The temperature distribution becomes an essential characteristic and must be determined independently of the actual reading. R. Geiger therefore proposed in presenting temperature observations near the ground, to use not calculated temperature points but bands of temperature, whose breadth corresponds to the range of distribution of the temperature for a given time at the place in question. This proposal has meanwhile been accepted and used in numerous publications.

Finally let us reach up in thought still further above the air layer near the ground and seek to understand the heating process at greater heights, for the stratification of unstable air masses is not without reaction upon the ground layer.

H. G. Koch (*133*) using a pair of pilot balloons, sent a radiation-shielded resistance thermometer up to 100 m and determined the temperature stratification within this air layer. He was able thus to demonstrate the great temperature disturbance which results from the heating process — "temperature gustiness" he calls it. In order to extend our consideration of the heating process also into these higher layers we have presented in Fig. 26 a fine example from Koch's work on the ascent of heated air from the ground. The upper curve of temperature state I shows the normal type of incoming radiation (Aug. 3, 1935 at 1050 A.M.). Shortly thereafter there was an upheaval in the stratification. It became warmer above, but noticeably colder in the ground layer. At first the mixing is imperfect; consequently curve II still shows a stratified structure of the air layer. Only after several minutes (curve III) is adjustment complete, with the temperature increasing uniformly with altitude.

The process of upheaval shown here coincided with the overshadowing of the measuring place by a cumulus cloud. Seven minutes after the cloud passed over, the incoming type of radiation I was re-established.

In conclusion we mention briefly the theoretical work of S. L. Malurkar and L. A. Ramdas (*134*) whose purpose it was to compute temperature stratification above heated ground from the heat balance and to test their calculations by observations.

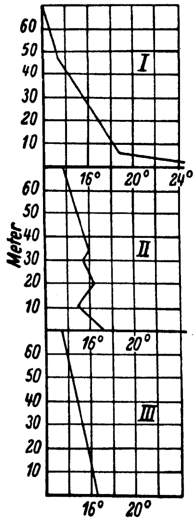

FIG. 26. Cooling of the layers of air near the ground by overturning of layers. (After H. G. Koch)

The assumptions which had to be made before attacking each theoretical problem are in the present case so few, and correspond so closely to the natural conditions, that the theoretical work can be treated here in close connection with practical microclimatic measurements.

It is assumed, namely, that:—

1. The heat balance, which is determined by radiational and eddy diffusion processes, has come to equilibrium; the temperatures are constant for a time, as occurs during the midday hours.

2. The water vapor content of the ground layer up to some 20 cm is uniform. This was tested by measurements with an Assmann psychrometer and found to be true at the place of measurement, a bare asphalt floor.

3. The temperature of the air masses lying above the ground layer can be looked upon as homogeneous, and finally,

4. No horizontal air transport (advection) is disturbing the heat balance.

The mathematical treatment takes into consideration the long-wave temperature radiation of the heated ground surface and all the air layers concerned—also the convection processes, under the conventional assumption that heat transfer is proportional to the vertical temperature gradient.

The computation leads to the following result:—Using the hyperbolic sine function,

$$\Phi = \Phi_0 \cdot \frac{\sinh \alpha (h + z)}{\sinh \alpha \cdot h}$$

z is the height in cm above the ground surface; h is the height of the ground layer concerned up to about 20 cm; Φ_0 is a constant; Φ is the variable part of the temperature. Since, for $z = h$, the value of $\Phi = 0$, Φ is the excess of temperature in the ground layer over the temperature value which was taken to be constant above the ground layer and which approaches the temperature curve asymp-

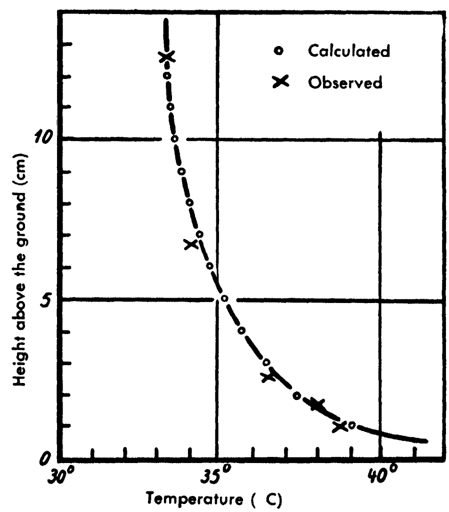

FIG. 27. Theoretically calculated and observed temperature stratification over an asphalt street. (After S. L. Malurkar and L. A. Ramdas)

totically as z increases. α is a coefficient in which are combined (a) the absorption coefficient of water vapor for long wave radiation, (b) the Stefan-Boltzmann constant, (c) the absolute temperature and (d) the austausch coefficient. The value of α varies. In the

highest layer, which extends from about 1 cm above the ground to some 30 cm, it amounts to 0.25. In the second layer, which extends from about 1 mm to 10 mm, it is 4.2. The change is discontinuous. Below 1 mm there is a layer with a still more suddenly increased α value.

Fig. 27 shows the temperatures measured by the author at 2 P.M. on Oct. 22, 1931 above an asphalt street near the Meteorological Office in Poona, using an Assmann aspiration psychrometer. The water vapor content of the air amounted to 10 mm. In addition there is a theoretical curve derived from the above given equation. The agreement of theory with observation is very good.

CHAPTER 7

The Cooling Process

The nocturnal cooling near the ground is a result of the outward radiation from the ground surface, which was described in Chapter 2. Even for some time before sunset the radiation balance of the ground is negative; in other words, the outgoing radiation exceeds the incoming. Nocturnal cooling consequently sets in before nightfall and lasts till after sunrise as E. G. Meyer (*149a*) has recently confirmed. Net outward radiation increases decidely as night comes on and reaches its maximum before midnight.

The ground surface cools through radiation. Along with the temperature decline of the surface goes the cooling of the air near it. Through radiative pseudo-conduction (Chapter 5) and pseudo heat conduction (Chapter 4) it gives heat to the colder ground. This loss is greatest for the layers nearest the surface and decreases with distance from the ground. Thus there is set up the outgoing radiation type shown in Fig. 8, in which the cold, and therefore heavy, air layers form beneath the warmer, lighter ones. In contrast to the incoming radiation type where the turmoil hinders stratification, a stable, vertical stratification predominates at night. This stability increases throughout the night as further cooling proceeds. G. Hellmann (59) has described this condition in these apt words: "The air clings to the ground as though anchored there, and resists all efforts to move it." Night is, consequently, the time of least wind velocity at the ground. Horizontal fog banks which last for hours unchanged, or slowly increasing in thickness, are often the visible manifestation of this stable stratification.

Nevertheless, at night a perceptible convection exists although diminished in comparison with the values during the day time. This is proved by observation. It is surprising at first glance; because the thermal exchange does not exist because of the stable air stratification and also the dynamic part is essentially diminished on account of the insignificant motion of the air. By night, however, another process occurs supporting the exchange to which A. Defant (*144*) drew our attention in 1919.

The dust content of the lower air layers increases at day time when the upward directed exchange currents lift the dust upward.

At night, a downward motion must occur because, otherwise, the dust content of the atmosphere would increase steadily. This sinking down is expected also from thermal causes. The dust which consists mostly of solid particles of the disintegrated soil absorbs altogether 5 to 15 percent of the incoming radiation during daytime. At night, it must play a similar part: the solid dust particles emit as does the solid surface and cool rapidly, therefore, below the temperature of the immediately surrounding air. This has a twofold effect: first, the air directly adjacent is cooled off. Because under normal conditions the air near the ground contains tens of thousands of dust particles per liter this kind of cooling process is not unimportant. Second, each dust particle together with the enveloping air film — the "small gas ball" — starts falling because of the lower temperature. Thus, a current of smallest air threads is fomed, called "returning convection" or "coldness convection" by A. Schmauss (*153*). There exists also during night, therefore, a thermally caused exchange. It is distinguished, however, from that in day time by the small dimensions of the portions of air which partake of the exchange. Therefore, it occurs to a certain extent unperceived in the stable air layers near the ground.

Besides the convection, processes caused by long wave radiation are effective as discussed in Chapter 5. These processes permit us to explain a striking phenomenon known from the tropics.

In 1932, L. A. Ramdas and S. Atmanathan (*152*) called attention to the fact that in India the lowest night temperature is in many cases not at the ground surface but at some distance above. Sometimes the minimum occurs at a height of only a few centimeters, but occasionally it may be as much as 1 m or more. Measurements at various places in India have proved this so many times that it can hardly be doubted. I know of no instance, however, of a similar valid observation in our climate, especially in Germany. The testimony of measurements which led to similar curves of state is inadmissible, since the slightest ground cover of plants naturally raises the minimum into the air, and since, too, even over bare ground, surrounding influences, such as a neighboring plant surface may occasion the same phenomenon. In addition, similar conditions in close proximity to the ground may be deceptive on account of difficulties in the technical use of instruments.

L. A. Ramdas, R. J. Kalamkar and K. M. Gadre (*191* and *192*) and later L. A. Ramdas (*151*) have made rather close estimates of minima above the surface. In Fig. 28 is given an example from a new piece of research by K. R. Ramanathan and L. A. Ramdas

(*150*). The measurements were made in the neighborhood of Poona on a January night in 1933. The temperature of the ground itself is indicated on the sketch by a small arrow coming from below. The small circle at zero height gives the air temperature measured directly at the surface; it is considerably lower than the surface temperature. From here on the temperature decreases with height still further up to a height of between 10 and 12 cm above the ground. Only above this begins the normal type of nocturnal outgoing radiation, the temperature inversion.

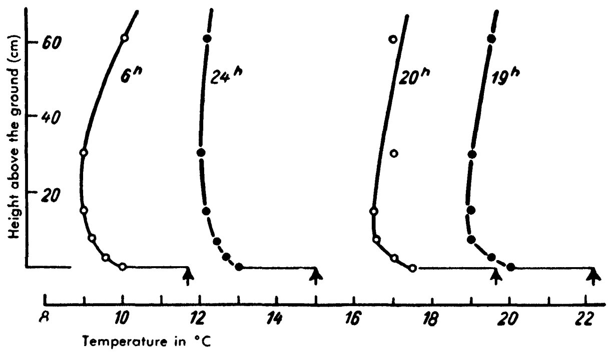

FIG. 28. Temperature variation with height during the night between January 5 and 6, 1933 near Poona. (After K. R. Ramanathan and L. A. Ramdas)

In the climate of India the heating of the ground by day is so excessive that at night there is a very strong flow of heat toward its surface. But even in an extreme case of this kind of a heat transfer, the minimum can occur above the surface only if the radiation processes, perhaps in conjunction with the stratification of the water vapor, displace the maximum zone of outward radiation from the ground surface into the airlayer above it. The work of K. R. Ramanathan and L. A. Ramdas already contains the theoretical research necessary to a solution of this question, and should be consulted for further details.

It remains our task here to show how the process of nocturnal cooling leads gradually to that temperature distribution which we recognize as the normal outgoing radiation type. Going beyond the province of the ground airlayer, we have already, in Fig. 20, shown the extension of the nocturnal temperature inversion to greater and greater heights. In what follows we shall limit ourselves to the region near the ground.

S. Siegel (*155*) assembled a wealth of observational data at Hamburg. On the grounds of the meteorological institute of the university, an observation tower was erected, with 22 measuring points arranged between the ground and a height of 4 m. At these points the nocturnal temperature was followed by means of radiation-shielded thermocouples. Fig. 29 shows several types of nocturnal temperature distribution according to altitude. The wind is assumed to be weak and the night favorable to radiation.

Curve 1, which Siegel calls the "evening wind type," starts at nightfall before the nocturnal calm has become established. The

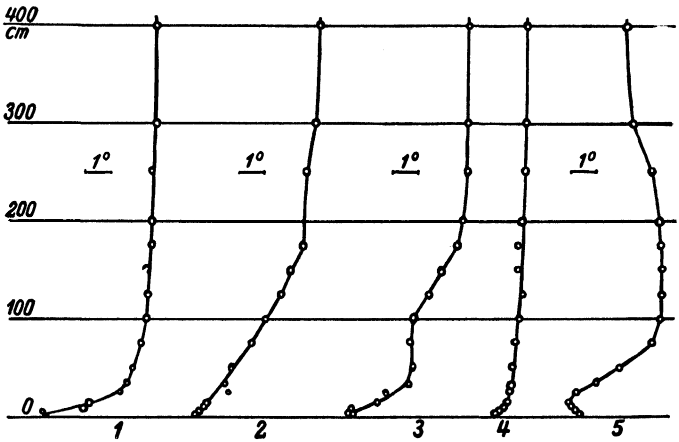

FIG. 29. Types of nocturnal temperature distribution over the ground. (After S. Siegel)

effect of outgoing radiation is yet noticeable only near the ground. Above this, practical isothermy prevails in consequence of the uniform mixing of the air. Only after the wind dies down does the intermediate type 2 take over. The cold layer deepens from below. A tolerably uniform fall of temperature is found up to a height of 1.5 m. At greater heights the temperature distribution is the same as for the evening wind type 1.

After the air has been quiet for 20 to 40 minutes we have type 2 passing into type 3, with a nocturnal secondary minimum. This is an indication that even at night the ground air has a foliated structure. The secondary minimum corresponds therefore to the secondary maximum of the day. When the wind rises suddenly at night a thorough mixing of the air is soon in process again with a conse-

quent equalization of temperature ("The wind prevents frost!"). The convection type 4 results.

In Fig. 29 the so-called "meadow-fog type" is given as type 5. It occurs when a thin sheet of fog 1 to 2 m thick forms over the meadows. A uniformly slowed cooling which Siegel attributes to condensation is evident within this layer. This warming up is superimposed on the outgoing radiation type and so appears in curve 5. At the Aspern airport in Vienna W. Kühnert (*149*), with a similar experimental setup, studied the temperature gradients above the ground during the slow growth of a fog bank. His work presents an opportunity to study the gradient fluctuations in relation to time and place, which are associated with ground-fog formation.

Fig. 30 shows in isopleths the ideal case of temperature stratification in the course of the night. At the upper edge of the chart is

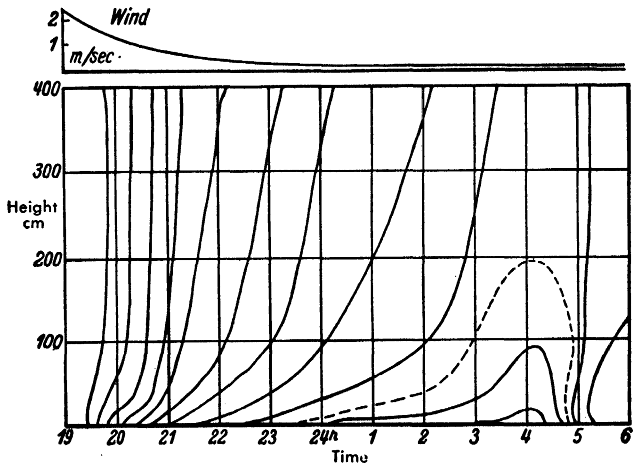

FIG. 30. Ideal case of the nocturnal temperature stratification over the ground. (After S. Siegel)

the idealized course of the wind velocity. The dying down of the wind in the evening causes the cooling off of the ground to be increasingly accelerated. As the night progresses the cold air layer at the ground builds up. It is most fully developed shortly before sunrise and usually disappears suddenly as the sun rises. Fig. 31 shows quite clearly what the actual thermal stratification is in certain cases. The picture in general is the same as in Fig. 30 but the course of the isotherms is much more irregular. If we compare them with

the curve for wind velocity that same night, as shown at the upper edge of the chart, we find that each time the wind dies down, the cold air layer builds up and each time the wind increases in strength

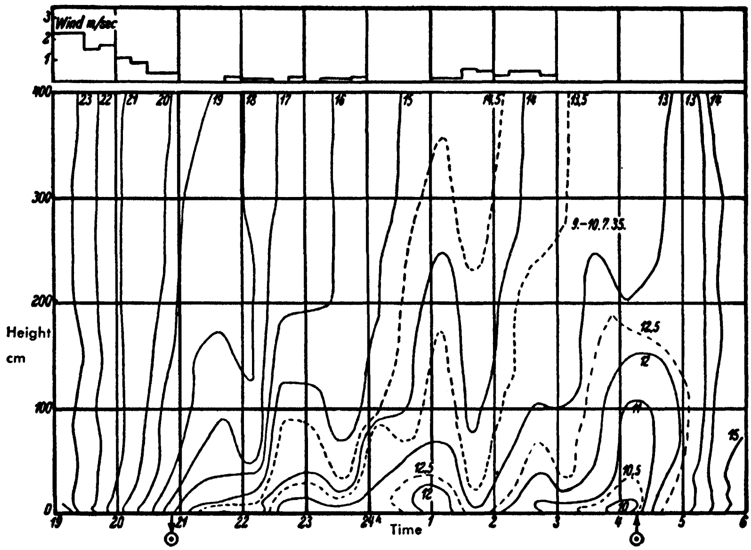

FIG. 31. Course of temperature on a night with light wind at Hamburg. (According to thermoelectric measurements at 23 heights above the ground by S. Siegel)

the stratification is destroyed. It follows that the disturbed state which we mentioned as a characteristic of temperature relationships in the microclimate is present by night as well as by day, though to a lesser degree.

CHAPTER 8

The Diurnal and Annual Course of Temperature Near the Ground

Our remarks thus far have been directed particularly toward an understanding of the physical laws governing heat stratification in the microclimatic air above the ground surface. How the heat transfer proceeds by day and night, how the heat is carried upward and downward from the boundary surface between earth and air, what contrasting temperature distributions present themselves as the incoming and outgoing types of radiation, these have been the subjects of our consideration.

Now, however, we must turn to the climatological side. Between the two extremes of temperature distribution mentioned above there are many transitional states. Transition is effected through the temporary change from one type to the other as sometimes happens during the morning hours. It is occasioned also by weather conditions which reinforce or reduce radiation in contrast to other factors such as wind or precipitation.

Whoever interests himself in the temperature relationships of the microclimate, seeks not only knowledge of the meteorological processes but also a description of the actual average conditions. It is our next task to present this.

For this purpose as long a series of observations as possible is desirable. Such a series is unfortunately very rare. Such as exist fall naturally into two distinct groups, which differ in the method of approach.

In the first place we seek to observe the "true air temperature." In the macroclimate we understand by this term that temperature which is indicated by some measuring instrument, such as a thermometer, which is in good contact with the air to be measured, while protected from all radiative influences. In practical climatology the measurement will be carried out in the standard shelter or with an aspiration psychrometer. The radiation shield, in the case of the shelter, consists of whitepainted walls and a double roof; in the case of the aspiration psychrometer, of a double-walled metal protecting cylinder which is polished nickel outside and blackened inside. Ventilation of the shelter through numerous openings in the walls, floor

and roof is fairly good. Ventilation of the aspiration psychrometer is accomplished artificially by means of clockwork. In the case of the sling psychrometer the instrument is moved through the air instead of the air being moved past the instrument. When protected from radiation it gives good results, at least so long as no precipitation is falling.

Measurements of the "true air-temperature" in this sense are also carried out as continuous records in proximity to the ground. For investigations in the larger space relationships it is possible to use observation shelters located at various heights and equipped with thermographs. The measurements given by K. Knoch (*185*) will serve as an example. As soon as we pass to smaller and smaller spaces we have to use electric thermometers — either resistance thermometers or thermocouples. The thermometers can be artificially shielded and ventilated. Representative in accuracy and general features of such measuring equipment are the investigations of N. K. Johnson (*182*) and W. D. Flower (*178*) of which more will be said later. Or, on the other hand, we can disregard both radiation shields and ventilation and, instead, use a resistance thermometer of such a small diameter that radiation errors can be neglected. Such was the fine resistance thermometer of F. Albrecht (*157*). In Figs. 22 and 23 we have already shown what excellent results Haude attained with this apparatus.

Albrecht's method has the advantage that the thermometer, on account of its small dimensions and mass, scarcely disturbs the natural temperature stratification at all, while artificial ventilation is entirely omitted. The disadvantage of the liability of the 0.015 mm platinum wire to mechanical damage can be offset by using a protecting cage. A. Mäde (*174*) described such a gadget which had practically no effect on the temperature readings. Unfortunately we have not as yet a long record with this apparatus from a ground air layer free from vegetation.

We are consequently using in the following discussion the diurnal and annual temperature march according to the measurements of N. K. Johnson and W. D. Flower. These data do not extend further than 1.2 m above the ground, so that the artificial ventilation is not a disadvantage in a comparison with the higher air state. A. C. Best (*176*) extended these researches, by means of the same method, through measurements at 30.0 cm and 2.5 cm above the ground. Although artificial ventilation at these low altitudes must necessarily result in mixing unequally warm air layers, and although conse-

quently the height of the place of measurement is not absolutely definite, we shall refer quite often to these measurements.

To summarize, let us say that in this chapter and the following one we shall deal with measurements of the *true* air temperature. Yet here we must mention a fundamental thought in this connection.

The "true air temperature" whose definition was a just and necessary precaution for macroclimatology, loses its significance as we approach the surface of the ground. As is evident from all that has been said, the neighborhood of the ground is characterized, in its effect on the microclimate, by the rapid decrease of natural ventilation and the decided increase of the effect of radiation. If by definition we reject radiation and demand thorough ventilation, we contradict the very nature of the ground climate.

While, therefore, physically minded meteorologists must have true air temperatures, even close to the ground, biologically minded students direct their attention to observed values which mean more in respect to biological processes. Plants and animals, insofar as they live near the ground, undergo these special conditions of high radiation and deficient ventilation. For biological purposes we are glad to use test objects. Their temperatures should be subject to the same kind, even if not to the same amounts, of radiation and wind as are the plants and animals themselves. The application of ground temperatures to the practical ends of gardening, agriculture and forestry has led to the use of experimental bodies, just as the application of macroclimatic temperature measurements to hygiene and biology have led to the use of the frigorimeter or frigorigraph, which basically are really test objects.

It is a question of scientific standardization how to judge the two viewpoints. The precise physicist will always have a horror of using artificial test objects where an immense number of inextricably involved separate factors are in play simultaneously. The practical botanist, on the other hand, can not understand why we measure an air temperature which, by its very definition, gives results far different from actual natural processes. The microclimatologist, who stands between the two camps, will perhaps consider it his purpose to measure all the factors involved, both singly and together, — true air temperature, humidity, wind, incoming and outgoing radiation of all wave lengths, reflected radiation, etc. Until this distant goal is attained the method of experimental bodies can not be entirely dispensed with.

J. Bartels and M. Köhn (*162*) report that J. Schubert used a thermograph as a test object. The measurements of P. Vujeric (*197*), inasmuch as they were made without a radiation shield, may be considered as measurement of experimental bodies. In the upper Bavarian station network R. Geiger (*179*) used Six's thermometer with transparent filling liquid whose overheating by day was comparatively slight. For continuous microclimatic records R. Geiger (*167*) introduced cylindrical electrical thermometers, which were also used occasionally by J. Bartels (*161*). Technical objections to this manner of using them in conjunction with recorders have been made by G. Gründl (*169*) and H. Forster (*165*), to which, in turn, the late F. Linke (*172*) took exception.

In Chapter 17 we shall introduce records from experimental bodies, but just now we shall turn our attention to measurements of the diurnal and annual march of the true air temperature at different heights above the ground.

N. K. Johnson (*182*) during the years 1923 to 1925, carried on measurements at heights of 1.2, 7.1 and 17.1 m above close-mown sod on Salisbury Plain, in southern England. He employed electric resistance thermometers which were perfectly shielded from radiation through six glazed porcelain casings arranged one over another in layers, and were artificially ventilated day and night. The thermometers were hung from a steel tower, constructed as light as possible. The tower was painted white to reduce its effect on the temperature field. The details of standardization of the apparatus should be obtained from the original publication which contains also the recorded data for the three years. A. C Best (*176*) has continued this research, making a record after the same manner, at heights of 30 cm and 2.5 cm from Aug. 1, 1931 to July 31, 1933.

The same arrangement was used by W. D. Flower (*178*) for observations which he has carried out since 1928 near the airship anchorage at Ismailia in Egypt (at the Suez canal). A special steel tower was erected near the anchor mast in that desertlike, almost flat land. Records were made at heights of 1.1, 16.2, 46.4 and 61.0 m. That from October 1931 to October 1932 has been worked out in detail. Flower had most favorable conditions for his experiment in the uniformly clear weather of Egypt; Johnson and Best's results correspond more closely to our climatic conditions.

In Fig. 32 the diurnal march of temperature in Egypt for the two contrasting months of January and July is shown as measured at heights of 1.1 m (solid line), 16.2 m (broken line) and 61.0 m

dotted line). In summer the incoming type of radiation; in winter, the outgoing type, occupies the greater portion of the day. During the summer nights the temperature difference between the several altitude layers continues to increase till sunrise; the three curves tend to separate. In the winter, on the contrary, a temperature gradient is established by midnight, which is maintained, even during the continued cooling.

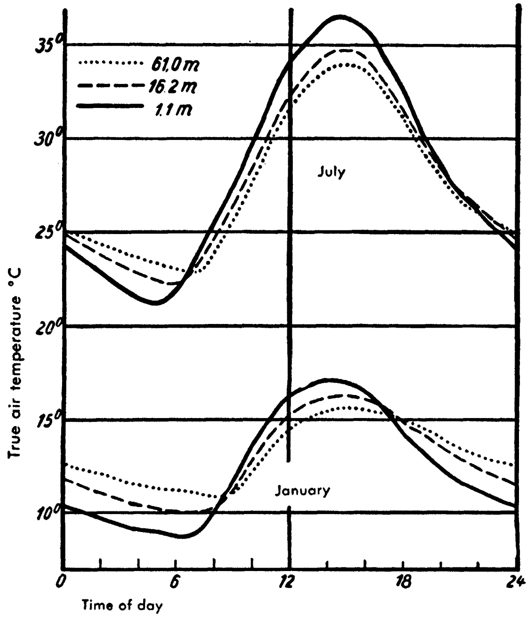

FIG. 32. Daily course of temperature in Ismailia (Egypt) in three different heights in January and July 1932. (After W. D. Flower)

In summer, as in winter, the temperature rise at the close of the night occurs at quite different times at the three different heights. In July, for instance, the minimum at 1.1 m is about 5 A.M.; at 16.2 m, shortly before 6; at 61.0 m not until about 7. As the beginning of the warming process is retarded with height, so does the maximum temperature occur later, the higher the measuring station is above the ground. In Fig. 32 this is most evident in January.

While the change from night to day always shows marked and regular retardation with height, the transition from day to night follows a different pattern. This is true not only for the measurements made in Egypt but as a general rule. The transition to the

nocturnal condition of stratification takes place almost simultaneously at all heights here considered. The way the temperature lines intersect is accidental rather than the result of strict regularity.

From the temperature scale of Fig. 32 it can be seen that the measurements are from a subtropical climate. In contrast, Fig. 33 shows the course of the temperature during a summer day in England. As is to be expected in a climate where insolation is weak,

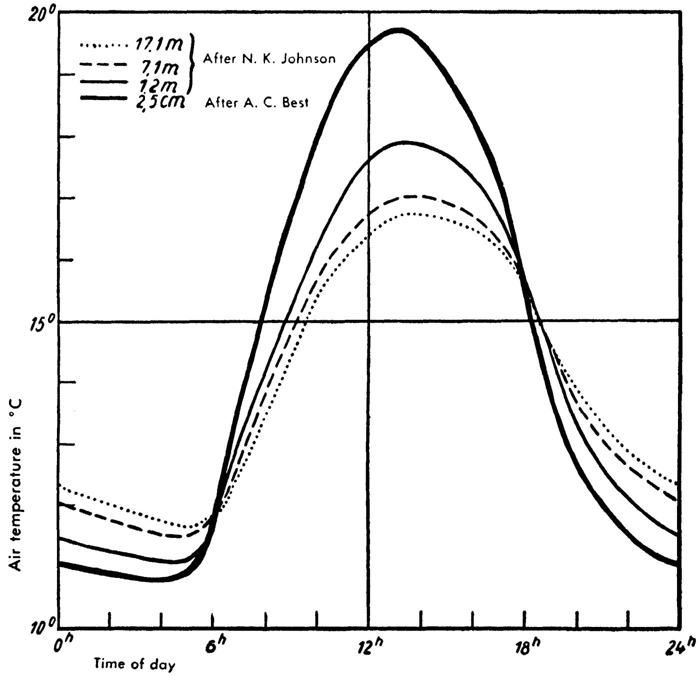

FIG. 33. Daily course of temperature in August, 1923–1925. (After Johnson and Best)

and at lesser heights above the ground, the temperature differences in the various layers are smaller throughout. (Notice the different temperature scale of the two charts!) The general features of Fig. 33, however, correspond to those of Fig. 32.

An example which brings us to the temperature stratification nearer the ground is shown in Fig. 34, from a publication by L. A. Ramdas and M. S. Katti (*210*). From measurements with an Assmann aspiration psychrometer the average values of hourly observations from the 4th to the 8th of January, 1933 are given in the form

of isopleths in steps of 2½ °C. The accompanying humidity distribution we shall study later in connection with Figs. 46 and 48.

In regard to the temperature stratification within the ground, the sketch reminds us of Fig. 10. The regularities found there reappear here too — i.e. decreased fluctuation of temperature, and lag of extreme values with depth. A very similar picture is formed by the isopleths above the ground, yet they, in contrast to conditions within the ground, are greatly elongated away from the surface. Here is

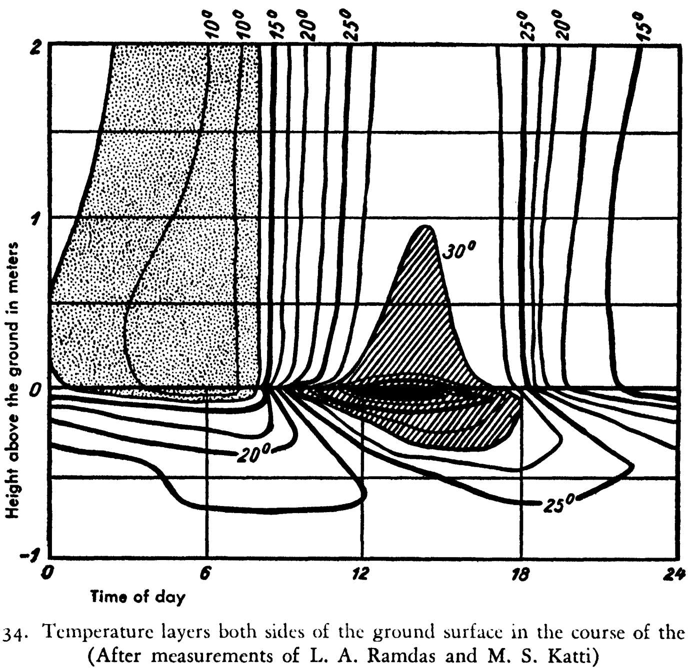

FIG. 34. Temperature layers both sides of the ground surface in the course of the day. (After measurements of L. A. Ramdas and M. S. Katti)

where the effect of eddy diffusion appears; the air behaves like a soil of extremely high conductivity. During the morning hours we find a cold-air dome, at midday, a warm-air dome, above the ground. During the afternoon temperatures at the ground rise to almost 50°. This could not be clearly shown in Fig. 34, since the region of time and place corresponding to these high temperatures is represented as a black area.

From the course of the daily temperature as depicted it follows that the daily range of temperature increases rapidly as we approach

the surface of the ground. At the Schleissheim observation station, the average daily temperature range for the months of May–September found by R. Geiger (*179*) was:—

Height above ground	1.5	1.0	0.5	0.05 m
Daily range	14.3	14.7	15.4	19.5°C

A. C. Best (*176*), using his records and those of N. K. Johnson over a period of two years, calculated the following average values of the daily temperature range in relation to height, season and weather:—

Height above ground	17.1	7.1	1.2	0.3	0.025 m
December Average	2.4	2.7	3.1	3.3	3.7°C
June Average	7.7	8.3	9.4	10.2	11.8°C
8 sunny June days	10.9	11.9	14.0	15.3	18.0°C

One of the particular characteristics of the microclimate is that it becomes more extreme the closer we approach the ground. Proof of this can be seen everywhere. Fig. 35 shows the railing of a flight of sandstone steps at the Winterthur city hall, in Switzerland, as published by F. de Quervain and M. Gschwind (*190*). The disintegration suffered by the soft stone increased with nearness to the ground. The great temperature range is here reinforced in its action by water. In the first place the lower part of the stone has been subjected to alternations between dryness and the moisture of snow and spattering rain more often than the upper part — another characteristic of the ground microclimate! Furthermore, in the transitional seasons, the destructive effect of frost through thawing and freezing is greater, the nearer the ground.

This change of melting and freezing again, the so called "frost change" is very different from place to place as far as the yearly frequency and its annual variation are concerned. Even with the large scale climate basic differences exist so that, now, the frequency of frost changes are considered a significant climatic element. Besides, the microclimatic differences are effective, for the mechanical formation of the ground, i.e. splitting of the rocks in consequence of the volume increase of water in the fissures when freezing, plays an important role.

A day with frost change is a day the temperature curve of which passes the freezing point one or several times independent of the

sense of the temperature change; if the temperature passes from positive to negative this process is connected with an explosive effect; changing from negative to positive is the condition for freezing again. *Number of frost changes* is the number of passages through the

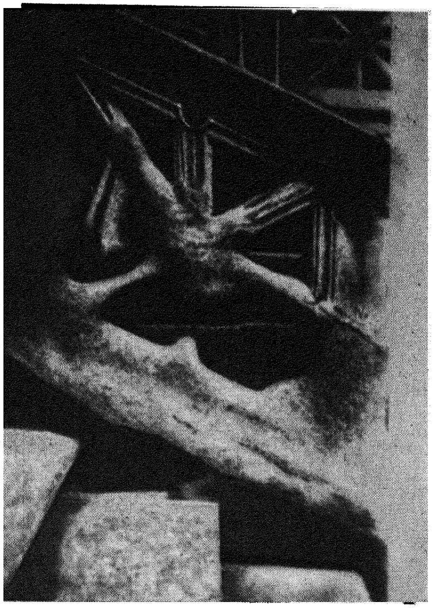

FIG. 35. Picture of the corrosion of the Bernese Sandstone on the State House in Winterthur. (After F. de Quervain and M. Gschwind)

freezing point. The number of frost changes is, therefore, equal to or greater than the number of days with frost change. The ratio of the two values which is $\geqq 1$ is called *density of frost change.* Its value is (in our latitudes) 1.5–2.0. In the high altitudes of the tropics the temperatures are above the freezing point during day time and below the freezing point with the same regularity at night in consequence of the uniform temperature the year round. The density of frost change results exactly with 2.0. It can even reach the value of 2.4 by supplementary irregular temperature variations.

The frost change is most frequent in the top layer of the ground. E. Heyer (*181*) found for Potsdam how the frost change number varies with depth:

Depth, cm:	0	2	5	10	50	100
Annual frost change number	119	78	47	24	3.5	0.3
Average frost change density:	1.8	1.8	1.7	1.5	1.1	1.0

From the synchronous temperature records in the shelter (1.9 m) he found a frost change number of 131, on the observation tower (34 m) 95; the frost change density was 1.8 at both points. The decrease of the frequency of frost changes from the surface downwards and upwards is easily recognizable, but systematic observations in the air layer near the surface are still lacking. As far as frost change frequency is concerned climatology at large scale and microclimatology approach one another closely.

In 1943 C. Troll (*196a*) made a thorough study on the importance and the geographical distribution of this climatic element and explained (1947) (*196b*) its effect upon soil formation. In the dry highlands of the tropical and semi-tropical mountain ranges rich in radiation the annual number of days with frost change surpasses 300 although the shelter temperature is used (for instance El Misti in South Peru (*337*). The frost change is, there, a whole year phenomenon; in higher latitudes it is limited to the transition seasons and winter. In many places soil structures with polygonal nets are caused by particular frost effects. The depth of these soil structures is only 10 to 20 cm in the high levels of the tropics, e. g. South Peru on the western slope of the Andes between 4100 and 5200 m, corresponding to the small depths to which the daily frost penetrates. But in the arctic regions, the order of magnitude of the depth of the soil structure is meters, corresponding to the deep reaching seasonal frost effects. But with these considerations we change to the realm of climatology on a large scale and soil science.

The increase of the daily temperature range with approach to the ground is common to all the macroclimates of the earth. This is to be expected in the tropics. But it is true of the polar climate also. The excellent observations of Alfred Wegener in Greenland have demonstrated the independence of the polar microclimate at the ground. More recently, H. Slanar (*195*) has carried out temperature measurement over a basalt ground surface in the polar wilderness of central Iceland during July 1931. As an average of five clear days he obtained a temperature range of 11°C at a height of 1 m and of at least 26°C at the ground. At a depth of 20 cm in the ground the range had diminished to 5°.

Now we shall show the influence of cloudiness on the daily temperature range in the air layer near the ground. The effect of the wind we shall take up later.

The observations of N. K. Johnson (*182*), which we present in Fig. 36, show very clearly the influence of changing weather on the temperature stratification above the ground surface. The summer

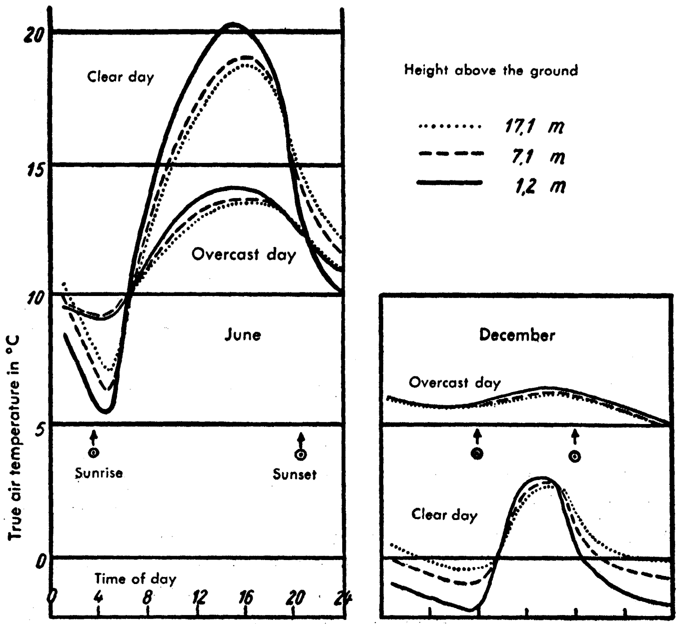

FIG. 36. Dependence of daily course of temperature on cloudiness. (After N. K. Johnson)

month of June and the winter month of December are placed side by side, using the same temperature scale. The times of sunrise and sunset are indicated by a small arrow attached to the recognized solar symbol. Cloudy weather in summer causes a decided flattening of the temperature curve. The average temperature, however, is only slightly reduced. The vertical temperature stratification is less, to be sure, but by day it is always evident. The displacement of the times of temperature extremes with height is greater in cloudy weather than in clear.

In December cloudy weather causes a decided rise of the whole temperature level. Clear weather brings frost. While on clear days

the outgoing type of radiation prevails for most of the day as a consequence of the long night, cloudy weather brings practical uniformity of night temperature. Only by day is there still some indication of a special microclimate above the ground. It should be noticed, nevertheless, that Fig. 36 shows nothing of the temperature relationships below 1.2 m. Many observations indicate that even in stormy weather there are still noteworthy temperature differences to be found there. Unfortunately we lack sufficient observations.

W. D. Flower has harmonically analyzed the annual temperature march for observation heights of 1.1, 16.2, 46.4 and 61.0 m above the ground. From the course of the temperature it appeared that at the four heights mentioned the peak values of the annual temperature curve fell on July 10, July 29, July 30, and July 31 respectively. By harmonic analysis of the diurnal march, the corresponding times of the temperature maxima were:—2:42, 3:17, 3:34 and 3:40 P.M. Thus the extension of the diurnal and annual temperature wave can still be recognized though so far away from the surface and through good measurements it can be traced as in the ground. It is really an unexpected pleasure to be able to demonstrate it so beautifully in the realm of the ground climate.

CHAPTER 9

The Temperature Gradient Near the Ground

In the free atmosphere, decrease of temperature with altitude is the rule. Temperature relationships near the ground, however, are characterized by change of the temperature gradient in direction and magnitude. It has been shown statistically what high values the

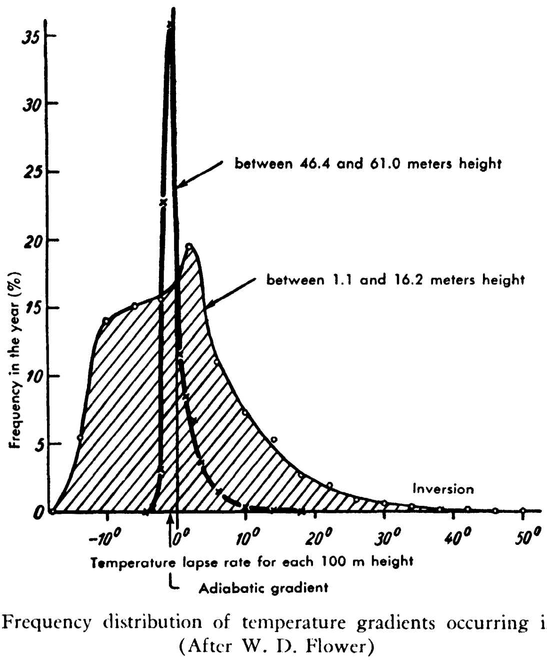

Fig. 37. Frequency distribution of temperature gradients occurring in Ismailia. (After W. D. Flower)

temperature gradient can attain at midday. W. D. Flower (*178*) in analyzing the Egyptian observations, as did N. K. Johnson (*182*) before him, paid particular attention to the variation of the temperature gradient with time. W. D. Flower's conclusions shall be our guide as to the most important facts in the following discussion.

Fig. 37 indicates, first of all, the frequency distribution of the most common gradients. As abscissa we have the gradient, computed in

altitude steps of 100 m each. Negative values mean the normal temperature decrease with altitude; positive mean inversions. As ordinate we have the annual percentage frequency computed as the mean from hourly values. The boundary curve of the shaded area represents the temperature gradients between 1.1 and 16.2 m above the ground. The heavy line represents gradients between heights of 46.4 and 61.0 m.

The shaded area is unsymmetrical with respect to the zero gradient. Slight inversions are the usual condition at these heights. The curve declines gradually to the right, for very large inversions are improbable but, on account of the stable stratification, still possible, and to the extent of almost 50° per 100 m. The adiabatic gradient is indicated by the arrow in the lower part of Fig. 37. There are super-adiabatic gradients far above this rate in the layer between 1 and 16 m. But once a value about ten times the adiabatic is reached, overturning occurs even in this very conservative ground layer. The frequency curve falls off steeply to the left of the −10° point.

In the more readily homogenized air between 46 and 61 m, by far the most frequent gradients lie between isothermy and the adiabatic value. Toward the left from this point the curve falls off very steeply since surplus heating from below is quickly equalized, with a return to the adiabatic gradient. Inversions still occur frequently.

The diurnal and annual cycle of temperature gradients is shown in Fig. 38. From 1893 to 1904 simultaneous records were made at the Meteorological Observatory in Potsdam, of temperature and humidity at the height of 2 m over a meadow and 34 m on a tower. K. Knoch (*185*) has analyzed the results. Fig. 38, accordingly, shows by isopleths the temperature difference between the two locations.

The time of year has been taken for abscissa, the time of day for ordinate. The continuous lines connect points of equal temperature difference between the 2 and 34 m heights. These differences are small since both records were made in shelters, thus avoiding extreme conditions. Negative numbers signify a normal decrease of temperature with height; positive numbers, an inversion. The two heavy zero lines indicate the condition of isothermy or what might well be called the transition from incoming to outgoing type of radiation and vice versa. The dotted lines correspond to the times of sunrise and sunset.

As has already been stated, the outgoing type lasts one or two hours after sunrise and takes over again about the same length of time before sunset. According to Fig. 38 difference of time is rela-

tively independent of the season, since the heavy zero lines and the dotted lines are practically parallel. In our latitude, the outgoing type occupies the greater amount of time; in winter it compresses the incoming type into a few midday hours.

In Fig. 38 the isopleths move far apart at night and stand vertically. The temperature difference between the upper and lower position

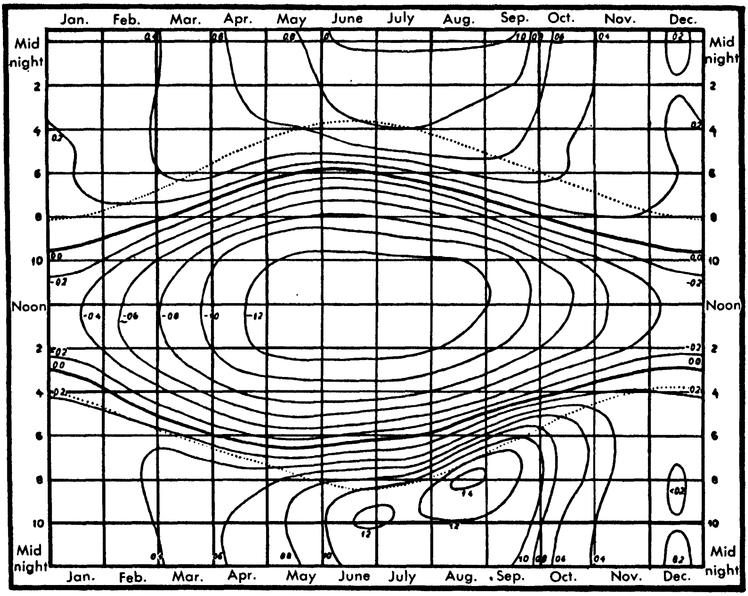

FIG. 38. Difference of the air temperature at 2 and 34 meters height in Potsdam 1893–1904. (After K. Knoch)

shows scarcely any change through the nocturnal hours of stable stratification, but in the daylight hours when the sun is actively effective it is quite otherwise; the horizontally lying isopleths lie close together. It is worth noticing that the course of the curves follows the dotted lines quite closely. It is sunrise and sunset which bring about the alteration in the heat balance in spite of the change from one type of radiation to the other occurring at a different hour. We shall later see (Fig. 41) that the transition is not always so regular in the ground climate.

Fig. 39 shows the daily change of the temperature gradients in three different parallel air layers, according to the observations of

W. D. Flower. In the uppermost layer between 46.4 and 61.0 m (dotted line), we find that in July there is a temperature inversion of 1½°C per 100 m before sunrise. Immediately after sunrise the gradient curve falls off but about 8 A.M. there is a sharp turn toward the horizontal. In this already freely moving air layer, as Fig. 37 has already demonstrated, the temperature gradient cannot significantly exceed the adiabatic value. Even in the underlying layer, down as low as 16.2 m the equalizing influence of convection can be easily recognized (dot-dash line, for layer from 16.2 to 46.4 m).

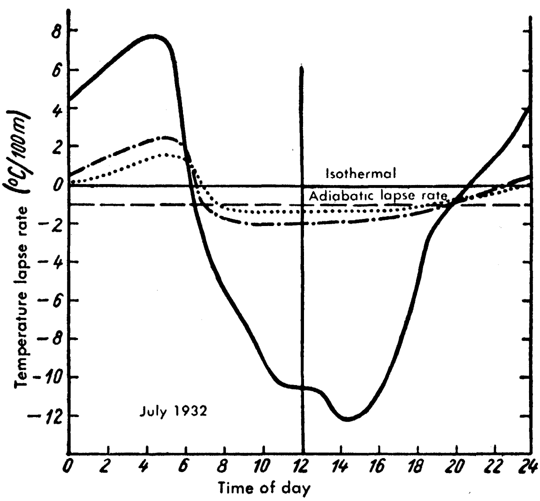

FIG. 39. Daily course of temperature gradients in Ismailia

Entirely different is the behavior of the air layer between 1.1 and 16.2 m (solid line). To be sure, the change between positive and negative temperature gradients occurs at the same time of day as in the higher layers. But the mobility of the air, which there exerts a moderating influence on the gradients, is lacking here. The gradients in both directions are excessive.

As we come still nearer to the ground, the gradients reach values of far more than 500° per 100 m. While the rate per 100 m naturally loses significance for such thin layers, it is nevertheless necessary in order to be able to compare the temperature gradients, independently of the apparent thickness of the layers. In the accompanying table derived from the measurements of Johnson (*182*) and Best (*176*) in England, we give an idea of the gradients at different heights and

TABLE 13

MEAN TEMPERATURE GRADIENTS IN THE GROUND AIR LAYER AFTER MEASUREMENTS BY N. K. JOHNSON AND A. C. BEST
(expressed in °C per 100 m)

Air layer	Time of day 2	4	6	8	10	12	14	16	18	20	22	24
January												
17.1–7.1 m	2.4	2.2	2.4	2.0	0.3	−1.0	−1.3	0.6	2.8	2.2	2.4	1.6
7.1–1.2 m	6.6	5.5	5.7	5.3	−1.4	−4.5	−2.0	3.2	8.4	8.5	7.2	7.3
1.2–0.3 m	24.7	33.4	21.0	17.3	−1.9	−7.4	−6.2	22.1	34.6	30.9	33.3	25.9
0.3–0.025 m	95	89	69	59	−46	−103	−36	103	143	121	115	109
July												
17.1–7.1 m	3.1	2.4	−0.6	−2.2	−3.1	−2.7	−3.0	−2.8	−1.3	3.8	2.6	2.8
7.1–1.2 m	9.9	8.5	−3.4	−10.5	−15.1	−17.3	−16.6	−12.5	−5.7	4.3	10.5	9.4
1.2–0.3 m	23.4	17.9	−1.9	−25.9	−38.3	−48.2	−45.7	−28.4	−5.6	21.0	25.9	25.3
0.3–0.025 m	55	30	−71	−362	−453	−503	−421	−244	−28	105	109	83

for different times of day in January and in July. The table is an excerpt from a compilation made by F. Steinhauser (*196*) in which data can be found for all months and hours of the day.

We shall now turn our attention particularly to the moment when the transition between incoming and outgoing types of radiation occurs. Here again we shall depend on the observations which W. D. Flower (*178*) made in Egypt.

In Fig. 40 the heavy line indicates the time of sunrise at Ismailia according to time of day and season. Quite regularly throughout

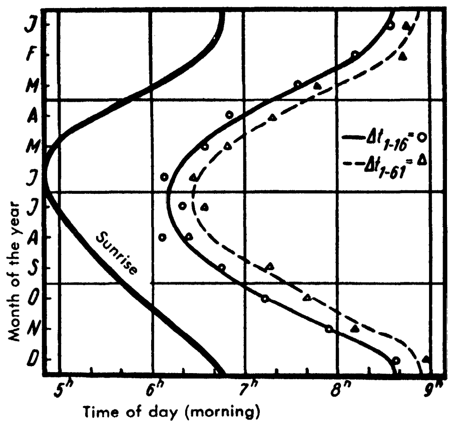

FIG. 40. Time of onset of the isothermal condition in the morning. (After the observations of W. D. Flower)

the year, at about 1½ hours after sunrise as a result of heating from below, the same temperature is reached at a height of 1 m as prevails at 16 m as a consequence of the nocturnal inversion. With as great regularity, about 20 minutes later, the measurements at 1 m and 61 m show equal temperatures.

At sunset the relationships are changed. From Fig. 41 we see that in the winter the outgoing radiation is so strong toward nightfall that the temperature gradient for the lower air layer has become zero by ½ hour before sunset. In summer, on the other hand, such an amount of heat is accumulated in the ground and the adjacent air layer in the course of the long day, that it is quite a while after sunset before the effective outgoing radiation at last makes its effect felt in the temperature gradient. The two curves, corresponding to the two air layers, are most widely separated during the months of May through August.

The cause of this difference between morning and evening conditions is this: At sunrise the air lies on the ground in a very stable state. By means of radiant solar energy it is upheaved from the ground. Knowing the vain attempts which technicians have made with heating apparatus to destroy the nocturnal inversion in the interest of frost protection, it is easier to comprehend the enormous work done by the sun every morning. The upset of the stratification proceeds rapidly and steadily upward in correspondence with the increasing warmth of the sun.

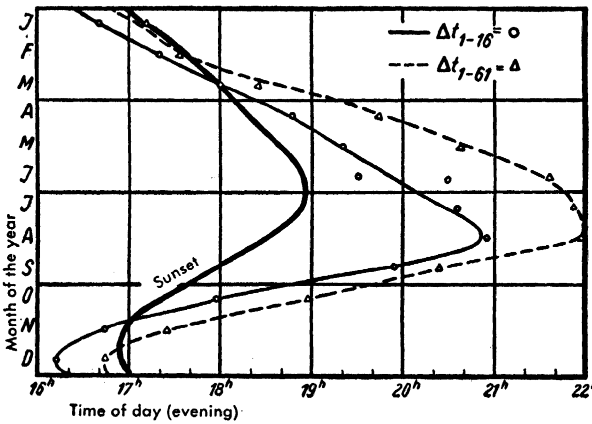

FIG. 41. Time of onset of the isothermal condition in the evening

When the sun goes down, on the other hand, the atmosphere is at first in relatively unstable stratification. Eddy diffusion becomes of less and less significance as time goes on. Radiative pseudo conduction takes its place. The ground gives up the heat stored during the day. The change in temperature stratification is brought about, not as by the powerful attack of a single all-compelling energy as is the case at sunrise; rather, the air layers become the sport of many factors and it depends on the accidental circumstances of the season what the total effect of the interplay of various forces amounts to. This is why the heat supply of the Egyptian ground in summer can postpone isothermy so long in the evening, while, as is shown in Fig. 38, the relationships are quite different in the hill and meadow lands near the Potsdam Observatory.

Referring to Fig. 42, let us consider how the time in the evening when isothermy occurs is related to humidity and wind velocity.

Once more the basic measurements are those of W. D. Flower (*178*), made on clear evenings for air layers between 1 and 16 m height.

The abscissa of the chart gives the number of minutes by which isothermy precedes or follows sunset. The ordinate is the magnitude t/e in which is combined the effect of temperature t as well as that of the vapor pressure of the air e. High humidity lessens the value of the expression, since e is in the denominator, so that a small ordinate value corresponds to a cool temperature and a high humidity. The three curves, which we shall first consider as a whole,

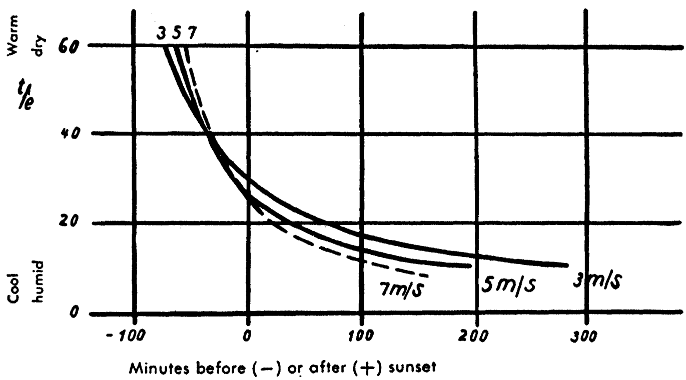

FIG. 42. Time of beginning of evening isothermal conditions in relation to temperature, humidity, and wind for the layer from 1 to 16 meter heights

demonstrate the fact that isothermy occurs earlier in the evening, the drier the air. This is readily understood, since dry air is associated with strong outgoing radiation. As the humidity increases it becomes increasingly longer after sundown before isothermy occurs.

The influence of the wind is clearly shown by the relation of the three curves to one another. High wind speed (7 m/sec) makes the curves steeper. This indicates that the influence of temperature and vapor pressure is less when the wind movement is lively. If, however, the wind is weak (3 m/sec) temperature and humidity have a greater effect.

During an evening fog, W. Kühnert (*149*) observed at the airport of Vienna the variation of the gradient in the layer near the ground up to 4 m height by means of thermocouples. Within the fog layer near the ground a temperature increase was found in the order of magnitude of 1°C per 1 m. In the same proportion as the radiation fog increased in thickness, the inversion layer also was increased;

it was formed, therefore, by air sinking down which was cooled by outgoing radiation at the upper surface of the fog. On the upper side of the fog the temperature increase with height was much smaller (order of magnitude 0.3°C per 1 m); isothermy or even an insignificant decrease of temperature with height was established.

A particularly fine example of the interrelation between temperature gradient and weather is afforded by the night's record at Ismailia on the 14th and 15th of April, 1932. The change of gradient during the night is there shown (Fig. 43). Fog began to form shortly before 3 A.M. The fog increased in density till about 8 A.M.

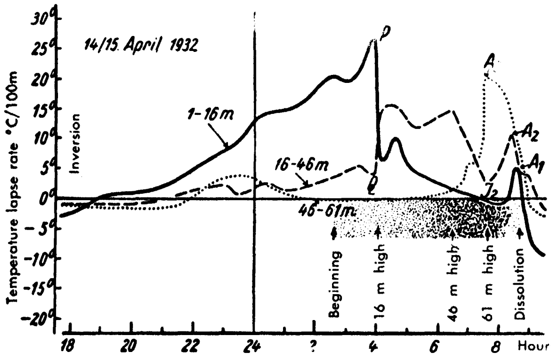

FIG. 43. Course of temperature gradients in morning fog at Ismailia. (After the observations of W. D. Flower)

but disappeared quickly as the sun rose. Let us first consider the course of the temperature gradient between the 1 and 16 m levels (heavy line).

In accordance with the normal nocturnal temperature fall, the gradient increases steadily till 4 A.M. The onset of fog formation makes no difference at first; but when, at about 4 A.M., the fog has reached a thickness of 16 m, the upper observation point becomes involved in it. The temperature gradient suddenly drops (point P) while at the same time the gradient between the 16 m and 46 m heights increases (point Q). This indicates that, under the influence of the fog, it suddenly became cold at the observation point in the 16 m level. From then on it belongs within the cold ground layer, within which the gradient decreases until point J_2, is reached.

When, at about 6:30 A.M. the fog reaches the 46 m level, the same act is repeated: the broken-line curve drops steeply, the dotted line

continues to climb. Under protection of the fog a minimum temperature gradient (J_2) is found toward the end of the night in the layer between 16 and 46 m.

Further development is stopped by the rising sun. The sun shines first on the upper sea of fog suddenly turning the upper gradient curve downward at A_3. Continued evaporation of the fog appears as a second shortlived increase of the inversion (Warming above!) in the broken-line and solid curves. Then they too turn down (Points A_2 and A_1) and pass into the incoming radiation type.

Further comments as to the relations between temperature gradients, wind gradients and wind velocity will appear in Chapter 11, where the wind relationships in the ground air layer are taken up.

SECTION III

OTHER METEOROLOGICAL ELEMENTS NEAR THE GROUND

CHAPTER 10

Humidity Relationships

Looking at the water balance of the atmosphere as a whole, we find that water vapor is furnished to the air only from the evaporating surfaces of the land and the water. Therein consists the great significance, for the water balance of the atmosphere, of the air layer next to the ground or the water. It is the producer and first transmitter of the water vapor of the air. When the upper layers thus become enriched and finally saturated with moisture, the condensing portion returns as precipitation to the earth's surface and is ready for another cycle.

Through evaporation at the surface, there follows directly an enrichment of the air with water vapor. Further transport upward in the air near the ground follows through eddy diffusion (Chapter 4) for, just as with heat transport it is not the true molecular conduction which is most important but rather mass exchange, so also for the transport of water vapor, it is not the molecular-physical process of diffusion which is important, but this same eddy diffusion.

The water vapor of the ground air layer, therefore, always comes from below. This, to be sure, is true for a definite place of observation only so long as no foreign influences intrude — according to the concept introduced by R. Geiger (*3a*), only so long as the climate is "independent." It is precisely in the small spaces with which microclimatology has to deal, that it is most evident how moister air and therefore excess vapor is created from propinquity. In such dependent climates, advection (the importation of water vapor) plays a part. We shall in the following paragraphs consider this very practical question.

The water loss of the ground determines the moisture relations of the air adjacent to it, just as its heat balance was affected by the ground surface. But while heat from the ground is transmitted to the air for one half of the day and for the other half it is returned by the air to the earth's surface, it is otherwise with the air's humid-

ity. Water vapor nearly always goes upward. Its return to the ground takes place almost entirely as another process, precipitation. It does happen in the very closest air to the ground that water vapor is led downwards to the soil, but even here, only under special conditions of dew formation. This process is confined to short night hours and its effectiveness as compared with the surrounding mass of water vapor is quite negligible in contrast to the normal process, by which the water vapor passes upward from the earth into the air.

So while temperature shows at one time a maximum at the earth's surface, and again, a minimum, the water vapor content of the air,

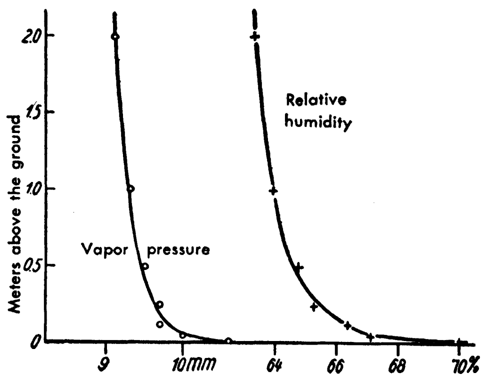

FIG. 44. Daily mean of the relative humidity and vapor pressure in relation to altitude. (After V. Rossi)

looking at it by and large, decreases steadily with height above the ground. This fundamental law holds, whether we consider vapor pressure measured in millimeters of mercury, or relative humidity, which is the ratio of the prevailing vapor pressure to the maximum possible at the existing temperature (the so-called saturation pressure) and which is expressed in percentage. Fig. 44 shows the variation of both magnitudes with altitude, for the lower 2 m of the atmosphere. The data are the daily average of the observations made by V. Rossi (*211*) at Lauttakylä, Finland from the 10th to the 16th of July, 1930, using thermocouple-psychrometers. The two curves show the rapid increase of both humidity values with approach to the ground. They remind one of the incoming radiation type when an overflow of heat is furnished by the earth's surface. Here, where water vapor is produced from below, we speak of a "wet type" of vertical moisture distribution.

The two wet type curves are based, as already mentioned, on the daily average. They are therefore only the result of a cross-section. Considering the relationships of all the times of day, we find that there is a dry type as well as a wet type. By "dry type" we mean a humidity distribution with respect to height, in which the air near the ground is dry and that above it is moist. The designation "dry type," just as that of "wet type," applies to both vapor pressure and relative humidity.

At what times and under what circumstances the dry type enters the picture depends on whether we are referring to the absolute or the relative humidity.

1. VARIATION OF VAPOR PRESSURE WITH HEIGHT DURING THE COURSE OF THE DAY

The amount of evaporation depends principally, according to a law of Dalton, on the temperature of the evaporating surface. The daily march of evaporation therefore parallels that of temperature. The high temperature of the ground by day sends so much water vapor from the ground air, with its extreme temperature range, into the overlying air, with its moderate range, that I know of no case in which the wet type does not predominate during the day.

By night the conditions change. The dew or frost which forms on the ground is derived, for the most part at least, from the water-vapor content of the air layers resting upon it. But even when there is no dew formed, the ground may absorb moisture, or evaporate it more slowly than capillarity brings it up, for, instead of the dry evening soil, we ordinarily find a moist surface in the morning.

At some time early in the night, therefore, there is a transition from wet to dry type of vapor pressure distribution in the ground air. Observations of H. E. Hamberg (*203*) made in the summer of 1875 in connection with his study of dew, show this drying out of the air layer near the ground. As an average of four July nights he obtained the following values of vapor pressure in millimeters in relation to height above ground and to time of day: —

TABLE 14

Height	Hour of the night 20½	21	22	23	24	1	4	5	6
At 31 m	7.7	7.9	7.6	7.7	**7.5**	**7.3**	**6.8**	**8.3**	9.0
At 12 m	7.8	8.0	7.8	***7.7***	7.3	7.1	6.6	8.0	9.1
At 0.3 m	7.8	8.2	**7.8**	7.6	7.2	7.0	6.5	7.8	9.3
At the ground	**8.3**	**8.4**	7.8	7.5	7.1	7.0	6.4	7.5	**9.5**

The maximum value for each hour of observation is shown in bold-face type. We see that in the evening the maximum is still at the ground. As dew begins to form the maximum moves quickly upward. After midnight it probably is higher than 31 m, for at that height the humidity is still decreasing till 4 A.M. Observations at greater heights are lacking. As soon as evaporation begins in the morning in place of condensation, the return of the maximum to the ground gives evidence of the wet type which characterizes daytime conditions.

We can thank M. Franssila (377) for some recent measurements in Finland. In the lower half of Fig. 45 which we shall next con-

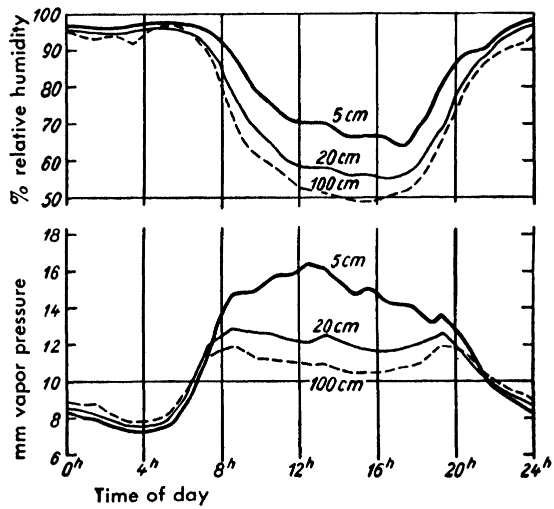

FIG. 45. Daily course of the relative humidity and vapor pressure in Finland. (After M. Franssila)

sider, there is represented the daily course of vapor pressure at three different distances above the ground. The measurements were made in the Pälkäne parish in Finland; the values shown are averaged from three August days in 1934. We notice first of all that the wet type shows a decided increase during the day, particularly around midday. The dry type prevails rather weakly from 10 P.M. to 7 A.M.

The lower part of Fig. 45 shows a further regularity. The broken line, which corresponds to a height of 1 m above the ground, shows the well-known double wave of vapor pressure. The principal minimum occurs in the morning at the same time as the temperature

minimum. A second, weaker minimum occurs in the early afternoon. This indicates that vigorous midday convection moves moist air upward from the ground and drier air downward. In the so-called "continental" or "desert" type of climate this midday minimum becomes the principal one.

Within the realm of the microclimate existing within 5 cm of the ground, the daily cycle of vapor pressure is a simple one. Instead of the secondary minimum there is a midday maximum. The reason for this is doubtless the fact that the weak convection does not reach quite to the ground and hence does not carry upwards the considerable amount of water vapor which is there available, consequently the maximum, which corresponds to the temperature maximum, and also the evaporation maximum, is maintained.

L. A. Ramdas (*209*) has furnished a record of vapor pressure relationships in the lower air at Poona, in southern India for the winters of 1933–37. From the measurements I have shown the average for the months of November–February. At this season the clear, undisturbed "winter" weather of India prevails — rich in radiation and unaffected by the ocean wind which comes with the spring. For nine different heights we get the following values: —

TABLE 15

Height above the ground in cm:	305	122	91	61	30	15	7.5	2.5	0.8
Vapor pressure in mm:									
At sunrise	8.8	8.2	8.0	7.8	7.6	7.5	7.4	7.4	7.5
At noon	8.3	8.5	8.6	8.7	8.9	9.0	9.4	9.6	10.0

At 3 m height the difference between the vapor pressure at sunrise and that at noon is only 0.5 mm. The slight difference is an indication that there is only one homogeneous air mass present at that season. Directly on the ground the difference between day and night amounts to five times as much (2.5 mm). By day it is moister on the ground than in the higher air; by night it is somewhat drier.

The measurements of H. Berg (*98*) also show the dry type at night. An instance is mentioned by S. Petterssen (*68*) of a case in which within the lowest 3½ m air layer there was a vapor pressure increase of 5.9 below and 10.4 mm above!

Finally, Fig. 46 shows by isopleths the daily course of the vapor pressure according to the observations of L. A. Ramdas and M. S. Katti (*210*). The concurrent temperature distribution has already been shown in Fig. 34. The 9 mm vapor pressure line arches up

above the ground at midday. The maximum height coincides not with the temperature maximum (Fig. 34) but with the radiation maximum. At night the air layer at 2 m above the ground shows the dry type, whose development becomes progressively stronger toward sunrise. As the sun rises, the air undergoes as sudden a

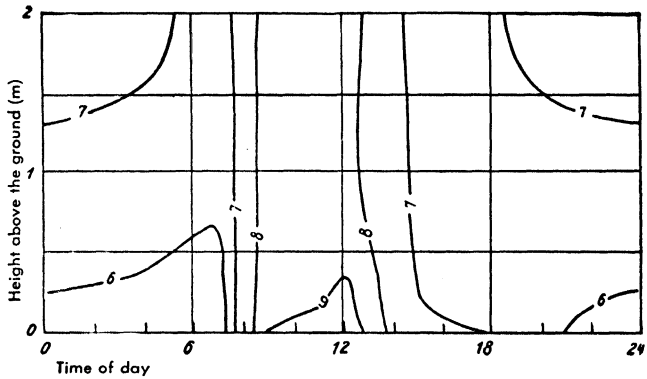

FIG. 46. Daily course of the vapor pressure in India. (After L. A. Ramdas and M. S. Katti)

change in water vapor content as we found, according to the measurements of S. Siegel, taking place at the distintegration of the nocturnal inversion.

We find measurements at greater heights in the old observations of S. A. Hill (*204*). There the daily march of vapor pressure at Allahabad is given in hourly values for the heights of 1.2, 14, 32 and 50 m.

In Fig. 49, where the daily humidity cycle in the ground air layer is represented according to types, only one type, the normal, is shown for vapor pressure. It will be quite different now, as we turn our attention to the relative humidity relationships.

2. VARIATION OF RELATIVE HUMIDITY WITH HEIGHT DURING THE COURSE OF THE DAY

The relative humidity is influenced by the absolute humidity as well as by temperature. If we imagine the water vapor content of the air unchanged, the daily course of the relative humidity is the converse of that of the temperature. In the ground air layer, the closer to the ground, the more extreme the temperature variation. Consequently the wet type prevails by night, the dry type by day. The in-

fluence of temperature on relative humidity is so compelling that this course of relative humidity represents the normal type.

For an example we first refer to the 12 year series of Potsdam observations at 2 and 34 m heights, studied by K. Knoch (*185*). In Fig. 47 we find the isopleths of relative humidity difference for all months and hours—just as Fig. 38 showed the temperature difference between the same heights. Most of the surface is occupied

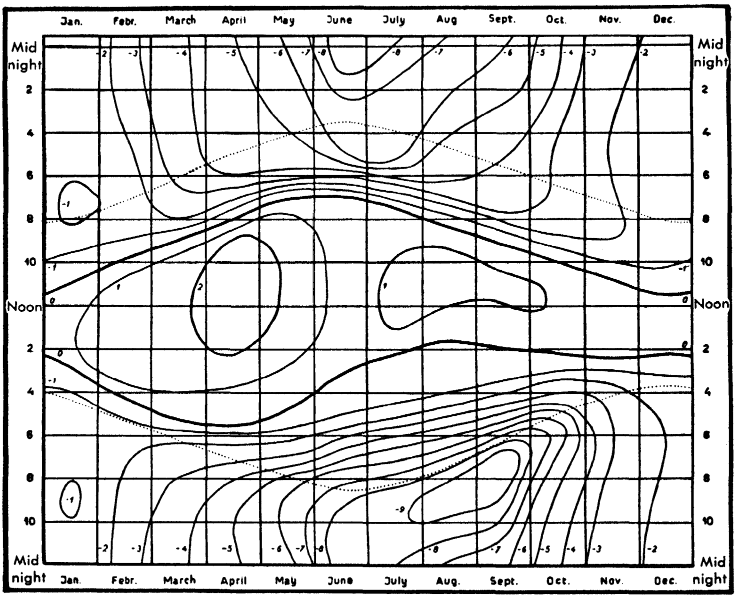

FIG. 47. Difference in relative humidity between the heights of 2 and 34 m. in Potsdam. (After K. Knoch)

by negative values; the wet type predominates. About the middle of the day, however, the dry type appears—being strongest in the dry spring months. While a difference of −9% is attained in the wet type, it is only in March and April that the dry type exceeds +2%. This is quite different from the temperature differences depicted in Fig. 38, which extended equally in each direction both by day and by night. Otherwise the curves approach closely, as did those of temperature, at sunrise and sunset, while the lines of equal humidity difference make right-angle bends at the times of transition between day and night.

There are two exceptions to this daily course of relative humidity in the microclimate, which in Fig. 49 is accepted as the normal type. They are occasioned by the effect of vapor pressure on the relative humidity.

In climatic provinces with low temperatures or high humidities, the wet type predominates throughout the day, even at midday. We can turn to Fig. 45 and see an example of this in the daily march of relative humidity at Pälkäne, Finland. At 5 cm above the ground the humidity even at noon is still 20% higher than at 1 m altitude. A contributing factor may be that these measurements were taken over clipped sod. D. Szymkiewicz (*213*) found something similar in his 1929 observations over a meadow in the Czerme peat bog. He found the mean relative humidity at 2:30 P.M. for the three summer months to be: —

TABLE 16

Height above ground in cm	Relative Humidity July	August	September
200	55	57	51
50	57	58	54
5	70	69	67

The second exception is found in climates with high temperature and low humidity. The Indian observations of L. A. Ramdas and M. S. Katti (*210*) will again serve as an example here. L. A. Ramdas (*209*) has called attention to the fact that the soil of India, particularly the black, cotton growing soil, has an extraordinary capacity for absorbing water vapor. With such enormously high noon temperatures the soil dries out greatly but at night it is able to withdraw large amounts of water vapor from the air layer resting upon it. By daily measurements of the moisture content of the ground surface from January to March, 1935, Ramdas found that the afternoon average water content in the soil was 3.8% as compared with 7.8% in the forenoon.

Fig. 48 shows the daily course of relative humidity in the air at 2 m above the ground just as the temperature is shown in Fig. 34 and the vapor pressure in Fig. 46. We find the dry type most prominent by day, as it is in our climate also. But even at night the drying effect of the ground on the lower air is so noticeable that even at the ground the relative humidity is somewhat lower than at a height of 2 m. Average values for the months November–February

gave a difference of 6% in relative humidity between the heights of 8 mm and 3 m. We can probably assume that this is seldom true.

Summarizing the data, we find a distribution of moisture in the air of the ground climate such as is shown schematically according

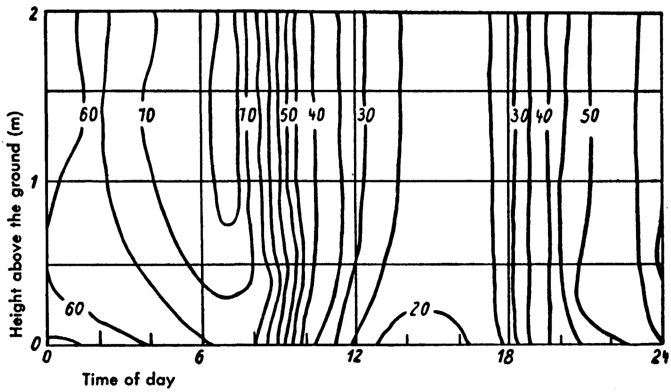

Fig. 48. Daily course of relative humidity in India (dry climate type)

to types in Fig. 49. For vapor pressure we have only the normal type. This is a combination of the wet type by day and the dry type by night. In the case of relative humidity, the normal is a combination of dry type by day and wet type by night. Here again we find two exceptions. The daily march of moisture distribution in which the wet type prevails is most deserving of the designation "wet climate type" of daily range. It is, as we saw, limited to moist and (or) cold regions. Correspondingly, we designate the exceptional type, in which the dry type of vertical moisture distribution is to be found during the whole day, as "dry climate type." It has been observed only in southern India.

In discussing temperature relationships, we mentioned great fluctuations and unsettled conditions of the temperature as one of the chief characteristics of the microclimate near the ground. This state of unrest which, in spite of high gradients, resulted from lack of convection, is likewise to be found in connection with humidity. Measurements which A. Büdel and R. Geiger (*199*) carried on in the neighborhood of Munich, showed sudden, violent fluctuations in relative humidity. Although the hygrometer which was used, on account of the length of hair, gave an average reading for a relatively large air layer, the quick succession of moist air masses

from below, and dry air masses from above could be noticed in the oscillations of the hygrometer pointer.

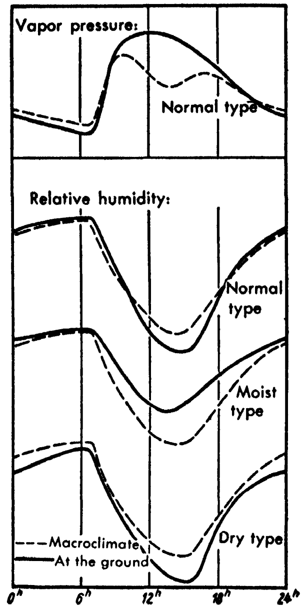

FIG. 49. Types of humidity distribution in the layer of air next to the ground

The following figures, taken, again, from the measurements of L. A. Ramdas (*209*) in Poona, will give some information on the daily fluctuation of humidity values in relation to height.

TABLE 17

Height above ground in cm	Average value for day (6 January 1933) Vapor pressure in mm	Average value for day (6 January 1933) Relative Humidity in %	Fluctuation during day in % of mean value Vapor pressure	Fluctuation during day in % of mean value Relative Humidity
305	7.0	48	9	54
92	7.1	48	12	55
7.5	6.8	43	20	56
0.8	7.1	40	21	63

The daily ranges of vapor pressure and relative humidity increase rapidly with approach to the ground, just as is the case with the temperature.

Reference should be made, in passing, to the manifold difficulties in adapting the technique of humidity measurement to the needs of microclimatology. The usual hair hygrometers fail to work in the ground air layer because they are too large; psychrometers because they require circulating air. In moisture measurement, then, technical difficulties arise from the same grounds as in the case of temperature measurement. The biologists in particular, often wish to measure humidity in very confined spaces, such as glass vessels in which imaginary conditions have been simulated. The publication by P. A. Buxton and K. Mellanby (*201*) gives an enlightening review of the biologists' needs in this respect. Today there are a number of solutions for this problem, no one of which can be considered entirely satisfactory.

A. Büdel (*199*) adapted the hair hygrometer, through a horizontal arrangement of the hair, to use in measurements near the ground. R. Geiger (*4*) published observations made by the use of this instrument, which show an extraordinarily pronounced stratification of humidity. D. E. Howell and R. Craig (*205*) (according to a reference in the 1940 bioclimatic supplement) describe a hair hygrometer whose most important part is the balance of a wrist watch. The dimensions of this instrument (6 x 8 x 0.5 cm) permit measurements in small spaces. V. Rossi (*211*) used thermocouples as a psychrometer. In 1932 H. Wald (*213a*) in Munich, developed the theory and technique of the electric psychrometer without artificial ventilation. W. Koch (*206*) also describes a similar arrangement. In a complete calm the psychrometric difference increases according to the decreasing diameter of the thermocouple used. By introducing the "wet" thermo-element into a porous clay tube of 1 mm diameter (better than a cloth covering) the psychrometric difference soon reached its maximum, which was not exceeded by later ventilation. This method, which was tested by Koch in the laboratory, has not yet, to my knowledge, been used in microclimatology.

Very recently E. T. Nielsen and H. M. Thamdrup (*208*) proposed a new method. If dilute sulphuric acid is in contact with air whose vapor pressure is greater than the saturation pressure of the acid, the air will give up water to the acid until equilibrium is attained and vice versa. The authors used small capillary tubes, 3 to 5 mm long, which were filled with sulphuric acid solutions of various con-

centrations, varying by steps corresponding to 5% on the humidity scale. These tubes could be introduced into very small research apparatus, such as glass jars, insect nests, etc. After 10 minutes it can be observed with a magnifier whether the liquid surface, which was just even with the end of the tube, has risen or fallen. From this the relative humidity is determined. The temperature error is negligibly small. It would be a great help in microclimatology if this new method should prove satisfactory.

CHAPTER 11

Wind Relationships

The most violent wind of the free atmosphere is to some extent slowed down by the ground. Directly at the surface, the air is entirely, or almost entirely, at rest. Through eddy diffusion the braking effect of the ground is transmitted upward, for each parcel of air which moves upward, carries with it the lesser horizontal motion which it possesses and, coming in contact with faster moving layers, exerts a braking action on them through its inertia. Conversely, each descending parcel of air carries down the higher velocity of the upper air currents. Just as through eddy diffusion the heat content, water content, dust content, etc. of the air is equalized upward and downward, so is it with the energy of motion.

The nearer to the ground, the more is all movement hindered. We have already recognized an instance of this in the "grinding up" of eddies at the ground. M. Franssila (*377*) has determined the air temperature at heights of 5, 20 and 100 cm above the ground by using an Assmann aspiration thermometer as well as electric resistance thermometers. The comparison proves that the air drawn in by the Assmann during the day comes, on the average, from an air layer 4 cm higher than that corresponding to the heights of the suction tube. The higher, more mobile air, therefore, flows more readily into the inlet tube than the lower lying, less mobile air; the suction is unsymmetric. When, at night, the air, as a result of temperature stratification, is at rest and cleaves tenaciously to the ground, the air drawn in originates in a layer even 10 cm higher.[1] This neat measurement of Franssila demonstrates the braking effect of the ground surface on air movement.

The air near the ground is the part of the atmosphere in particular where wind velocity shows a great increase with height. A glance at the rime formation shown in Fig. 50 shows this strikingly. As is well known, rime results from the deposition of supercooled water drops floating in a driving fog which are carried by the wind against some solid object. The size of the rime flags which grow

[1] On this account J. Bartels (*160*) proposed moving slowly forward with the Assmann so that the orifice of the suction tube could be kept constantly at the desired height.

against the wind is greater, the more drops freeze on in a given time. This, in turn, depends on the wind velocity. It is not unusual for the flags to grow according to their height above ground as Fig. 50 shows them on telegraph poles. The deposition of rime can be regarded as a natural record of wind velocity.

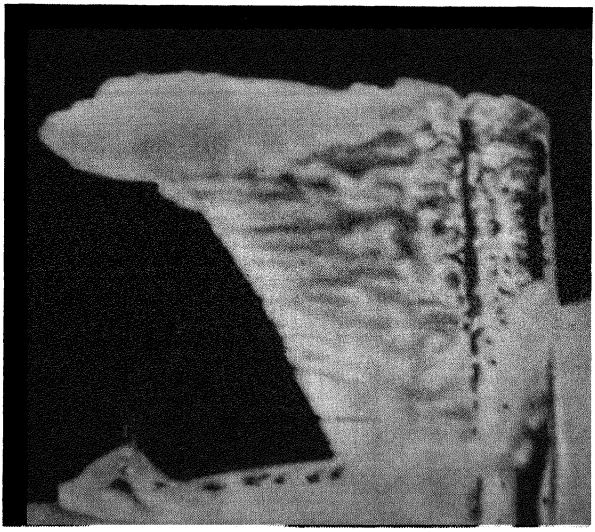

FIG. 50. Rime banner, which demonstrates the increase of wind speed with height above the ground. (Photographed on Mt. Washington)

For all practical purposes the variation of wind velocity with height can be expressed in this simple equation:—

$$v_2 = v_1 \cdot z^a$$

v_2 signifies the wind velocity in m per sec at the height of z meters; v_1, the velocity at a height of 1 m. a is an exponent whose value must be determined from observations on the actual variation of wind with height.

G. Hellmann (*216*) was probably the first to carry on systematic measurements of wind velocity in the ground air. He located registering anemometers on the Nuthe meadows at Potsdam, at elevations of 5, 25, 50, 100 and 200 cm. The anemometers were at least 4 m apart horizontally, in order to avoid mutual interference. The

experiment lasted from July to October, 1918; there was a total of 1488 hours' record.

Fig. 51 gives the results. If we express the above-stated equation logarithmically, then

$$\log v_2 - \log v_1 = a \log z$$

In the logarithmic system of coordinates, such as that chosen for Fig. 51, the curve of state therefore appears as a straight line. Con-

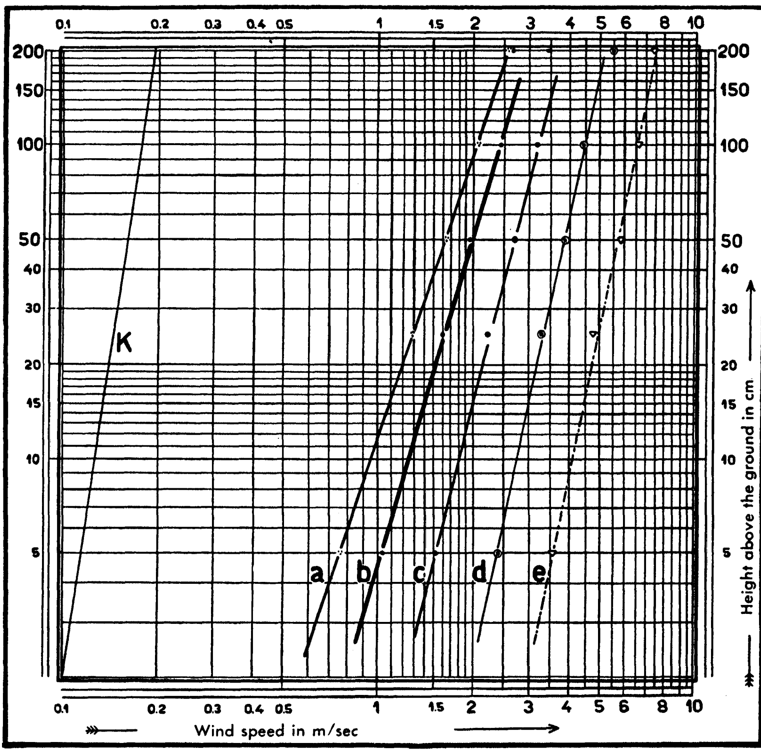

FIG. 51. Variation of wind speed with altitude

versely, if the law is actually fulfilled, all observed values must lie on straight lines. We see that this requirement is substantially fulfilled by the observations. The line *b* represents the mean value of the 1488 hours; *a* and *c*, the same values separated into the calm hours of the night and the windy hours of the day. Observations on

the windiest day are located along line *d*; those during the windiest hour (Sept. 30, 1918, from 10 to 11 P.M.), along line *e*.

The value of the exponent α is equal to the tangent of the angle at which the straight line is inclined to the ordinate. In Fig. 51, $\alpha = 0.3$. The inclination of the line *K* corresponds to the value, $\alpha = 1/7$; this is the lowest value thus far observed.

The value of α, as has already been mentioned, is not constant. It depends principally on height, for with increasing height the effect of ground friction diminishes, and consequently α becomes smaller. G. Hellmann (*217*) showed, however, in reference to the air near the ground that, for at least the lowest 1½ m, α may be considered constant.

O. G. Sutton (*231*) has emphasized the dependence of the exponent α on the temperature gradient. He calculated the daily range of the exponent, from the observations of G. S. P. Heywood (*218*). The wind measurements used were at heights of 12.7 and 94.5 m above the ground at Leafield. During the summer (April through September) the change of exponent from midday to midnight was from 0.07 to 0.17. During the winter (October through March) the corresponding values were 0.08 and 0.13. This range seems slight. B. Ali (*215*) found a large range in observations made at Agra, in India. A. C. Best (*176*) in a recent thorough investigation of wind variation with height and wind structure near the ground, has determined the increase of velocity in relation to simultaneously occurring temperature gradients. Since this research touches on the peculiar province of the microclimate, it has particular interest for us. The following figures give the average wind speeds for the lowest 2 m, expressed in percentage of the speed at 1 m. When the temperature decreases decidedly with height (as in

TABLE 18

Temperature gradient	Height above ground in cm						
	2.5	5	10	25	50	100	200
	Wind speed (in % of wind speed at 1 m height)						
−3°F/m (Temperature decrease)	43	52	67	81	90	100	107
0 (isothermy)	36	49	63	79	90	100	112
+1°F/m (Inversion)	34	48	60	77	89	100	114

line 1), the variation of wind with height is less than in the case of an inversion (line 3). A. C. Best rightly remarks that it is quite impossible to separate the effects of temperature gradient and wind

gradient, for they mutually affect and determine one another. We shall return to this question when considering Fig. 59.

Besides the above mentioned research of G. Hellmann, we have older measurements by Th. Stevenson (*230*) which have been made accessible through the work of W. Schmidt (*228*). A. Peppler (*225*) has also determined wind variation with height through observations on the Eilveser radio tower. The most recent and careful investigations in the air near the ground we owe to W. Paeschke (*224*). He has, in particular, made a comparison of all available measurements as to the dependence of the exponent a on the ground cover. It appears that, in general, a lies between 1/5 and 1/3. The value 1/5 occurs above a snow cover, which offers least resistance to the wind. The upper limit of 1/3 was obtained over a turnip field. We shall return to this in Chapter 28. The largest value for a, of which I know in the literature, is that of 0.46, given by B. Ali (*215*); the smallest (0.07) has been mentioned above.

The numerical values for a make it possible, if we know the wind speed at one height, to calculate it for any other height within the ground air layer. A graphic method such as that shown in Fig. 51, is useful. It should be noted, however, that for microclimatic measurements, a height of 1 m above the ground has been taken as normal. It is desirable in all kinds of investigations, first to locate the anemometer at this height in order to avoid corrections so far as possible.

Finally it should be emphasized that the law of wind variation with height, as stated, is only a *statistical* law. It holds good in a long series of observations, but not necessarily in individual instances. G. Hellmann (*217*) remarked that "small currents of faster moving air often underlie others with lower velocity." Great variation in the values of the exponent a were found by P. Michaelis (*343a*) in wind velocity measurements over a snow cover in the little Walser valley (Alhgäu Alps). Fig. 52 shows examples published by W. Schmidt (*817*). The upper half of Fig. 52 (*a*) represents wind variation with height on the night of May 10–11, 1928, in the neighborhood of Vienna. In the air layer from the ground up to 2 m, there is low wind speed with no regular dependence on height apparent. Above this level a strong wind is blowing. The lower half of Fig. 52 shows four examples from the following night, on which frost occurred. At about 8 P.M. (*b*) there was an almost linear increase in wind speed from 0.6 m per sec at the ground to 1.8 m per sec at a height of 7 m. A half hour later (*c*) there was a calm at 7 m while the layer within 2 m of the ground was the

one in most lively motion. Thus quickly does the picture of wind velocity distribution change. Here also the "stratified structure" of the ground air is strikingly in evidence.

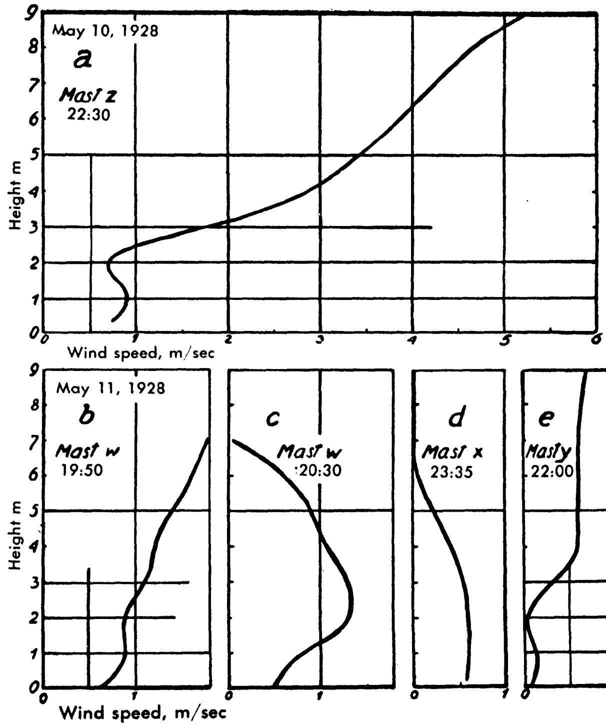

FIG. 52. Irregular wind stratification above the ground. (Measurements by Wilh. Schmidt)

It is of great significance for microclimatology that F. Albrecht (*214*) has built a hot wire anemometer which is very suitably designed for field work in meteorology. By means of this instrument it is possible to make direct measurements of the lowest wind speeds with great accuracy. W. Viereck (*233*) has described a recording wind apparatus based on the hot wire principle. Details of its applications are lacking.

Now we shall turn to the daily range of wind velocity in the ground air.

It is known that near the ground a maximum of wind velocity is found at about midday, while at night the strength of the wind usually diminishes. A. Wagner (*234*) has shown that it is not eddy diffusion which accounts for this range, which is directly the opposite of that in the higher air layers. Although eddy diffusion is stronger at midday, yet stronger eddy diffusion means only stronger braking effect. It is rather caused by the greater increase of eddy diffusion with height in the middle of the day as contrasted with less increase by night.

Fig. 53 is a graphic representation of the already mentioned measurements by G. Hellmann (*217*) of the daily range of wind velocity at various heights above the ground. It clearly shows the midday

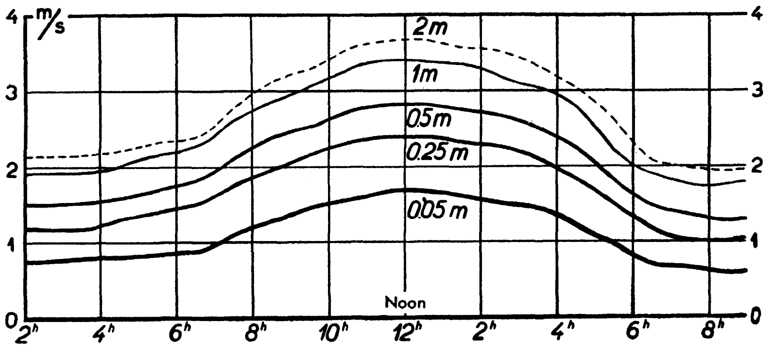

FIG. 53. Daily course of the wind speed at various altitudes. (After G. Hellmann)

maximum and the nocturnal calm in all layers. For practical questions, especially in plant physiology, it is noteworthy that the time when quiet hours predominate gets longer with approach to the earth's surface. In Fig. 54 the number of calm hours according to Hellmann's observations is shown as percentage of all the recorded hours in their relation to height and time of day. The calms are more numerous the darker the shading. It is plain how the midday increase of wind velocity is much less pronounced near the ground. In the transitional hours of morning and evening, the nocturnal calm close to the earth extends into the daylight hours.

Here, a particular property of the air layer near the ground should be mentioned which is in close correlation with the wind conditions. Strong wind is able to lift up and carry away loose particles of the ground such as dust, loess, sand or snow. Dust at first decreases the visibility; then one speaks of *sand-sweep* and *snow-sweep* as

long as the particles drift along so close to the ground as not to hinder the horizontal visibility greatly; with further increase of the wind, *drifting sand* or *drifting snow* decrease the visibility. If snowfall joins the drift we speak of a snowstorm.

W. Haude (*426a*) gives the following description of sand drifting high up around the winter camp of Edsengol (Gobi Desert): "Turbidity of the air by dust and sand starts when the wind freshens up above a certain threshold which naturally is lower with dust whirling than with sand and even with coarse gravels. During day time, the threshold is also lower than at night. Everywhere where terminal lakes exist into which the streams empty, at least temporarily, the water of which is enriched by finest silt, great quanti-

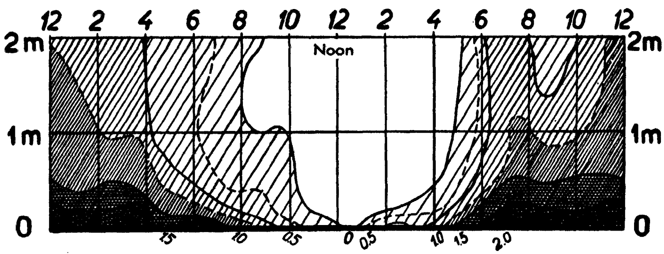

FIG. 54. Frequency of calm hours in the air layer near the ground

ties of finest dust particles are available on areas occasionally or previously inundated. Naturally, it is here most likely that great quantities of silt are whirled up. Freshening wind meets here smallest particles which can be carried along. As a consequence the decrease in visibility is the most intense in the immediate vicinity of the terminal lakes. This is true near the Gaschuun-nor and Koko-nor and is the most strongly marked at the Lob-nor (chara buran, black storm).

"Thus, at the Edsen-gol, a hazy banner cloud could be observed north of the terminal lake region which developed mostly in the morning of many days. The manner in which it developed and changed was one of the obvious indications of the beginning of sand drift. When the dust cloud grew rapidly, drifting sand could be counted upon to start soon, since in the region of Edsen-gol sand was abundant. While on the crest of the dunes the well-known whirls and eddies occurred, drifting of sand near the ground developed on the area with gravel. At eye level, the visibility remained still good, while near the ground, large masses of sand were moved

along the fields over the gravel ground according to the intensity of the individual wind squalls. With each more intense squall long chains of dust approached, which, however, did not reach a greater height. Concavely curved on the front, they moved over the free gravel surface carrying with them a long trail of dust but taking off only few dust particles from the gravel area. The motion was mostly in straight lines; only now and then, small variations of the direction for only a few degrees could be observed. Sometimes, a subsequent dust wave had a somewhat other direction than the preceding one."

It is now of a special microclimatic interest how he describes the transition from this winter-time drifting sand to the first small spout (see page 9) in earliest spring when the daily temperature variation was intensified: "During the last days of January, a change of this echelonlike straight forward movement set in. With the individual squalls a trace of rotation could be seen. Seemingly, it was developed incompletely, so that a circular shape was seen clearly only in the highest-lifted dust. In the beginning of February, however, some squalls represented already genuine small spouts and were seen within some of the described straight lined dust squalls; or they occurred independently when the general wind speed had decreased. Their appearance occurred between 10 and noon. The radiation had become already so effective that the heating of the ground caused superheating of the lowest air layers. Most frequently, however, the motion of the air must reach a certain speed to cause their development."

Fig. 55 is a reproduction of a photograph by P. Michaelis (*344*). The pine shown is growing at timber line in the Allgäu Alps. The dotted line indicates the position of the snow surface in winter. The growth of the tree shows the influence of the two-fold surface. The entire absence of branches on the right, just above the winter surface, shows the abrasive effect of the wind, loaded with drifting snow. The trunk lacks the growth of lichens which elsewhere are abundant; often the bark is deeply cracked. This is the north side. On the south side, however, which, in the photo, is at the left, the branches, though withered, are still present in part as dead wood covered with lichens. The great fluctuation of temperature above the highly reflecting snow cover is to blame for this damage.

In conclusion it is our task to point out the influence of the wind on the temperature of the ground-air.

Higher wind velocity means, as we have seen, increased dynamic convection. Increased convection results in decreased temperature

gradients. This means lower temperature at the ground by day, and higher at night. It is the night effect which is of great practical importance. The farmer is not afraid of frost when there is wind, but he is, if the wind goes down with the sun.

F. Katheder (219) tells of the following observation: On September 23, 1936, just after 6 P.M. a shallow fog, 1 to 1½ m thick formed

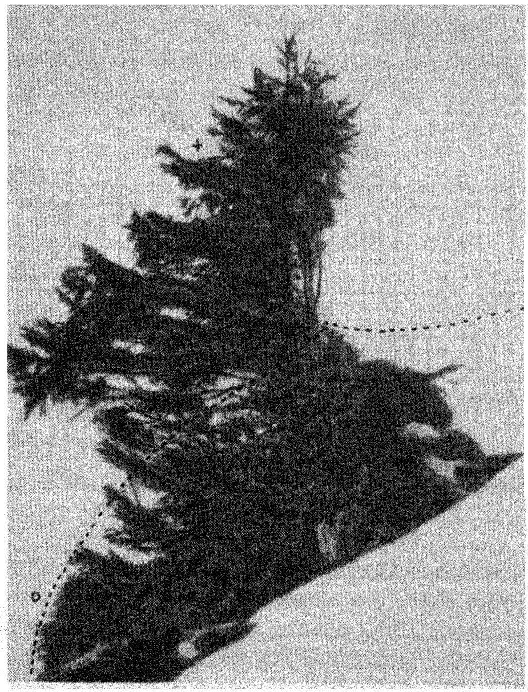

FIG. 55. The microclimatic damage on this alpine fir tree above the winter (dotted line) snow cover is evident. (Photograph by P. Michaelis in Allgäu)

in the quiet air covering the ground at the Nuremberg airport. Above this layer there was excellent visibility. In the instrument shelter 2 m above the ground the relative humidity was 86%, the air temperature, 15.2°. The ground temperature was about 12°. At 6:40 a three-motored Junkers started on its scheduled trip to Munich. "During the take-off there was formed along the runway behind the plane a channel entirely free of fog. In the course of four or five minutes the sharp boundary between fog and fog-free space disappeared and

after a short time the original condition again prevailed. The width of the clear channel was just about the span of the Junkers." The stirring up of the ground air by the three propellers of the plane in this case brought warmer and drier air down from above. Perhaps the hot exhaust gases had something to do with the temporary fog dispersal. It was a visible demonstration of the law we have stated.

The effect of the wind in raising the temperature is not limited to the air near the ground. We shall first take an example from the more abundant data at normal heights. A. G. McAdie's record (222) reproduced in Fig. 56 covers three nights with uniform

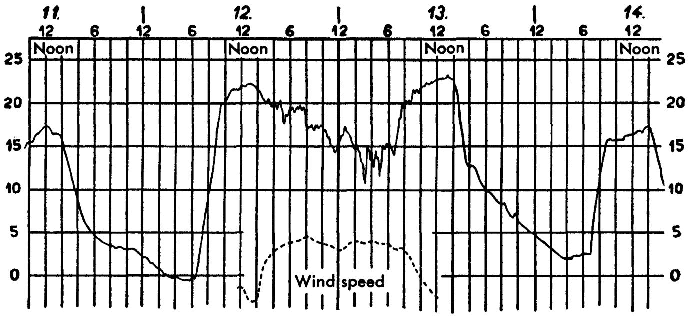

Fig. 56. Night temperatures at Kentfield in California from 11th to 14th of December 1911. (After A. G. McAdie)

weather conditions. Between the calm nights of December 11–12 and 13–14, 1911 there was one with a brisk wind. The wind measurements recorded at the nearest station are reproduced at the lower edge of the chart, and show the increase in strength of the wind from 2 P.M. on the 12th until about noon the next day. Now while the temperature reached 0°C the preceding night and almost as low on the night following, the wind, whose fluctuations are apparent in the temperature curve, kept the temperature above 10° on the 12th and 13th.

Fig. 57 refers to the fruit growing district of Los Angeles, California. The district is bounded on the north by the San Gabriel and San Bernardino mountains, between which lies the Cajon Pass. The night of January 19–20, 1922, brought a heavy, killing frost to the whole region. F. D. Young (235) has furnished the temperature minima observed in numerous orange groves; the figures naturally vary with the locations. If we treat them in small groups so as to

screen out local influences we get a unified picture. On the sketch the nocturnal minima (in C°) are given in oblique figures; the small adjacent figures indicate the number of observations from which the values are averaged.

By drawing the broken-line isotherms it becomes very evident that in the areas where the wind blowing through the Cajon Pass

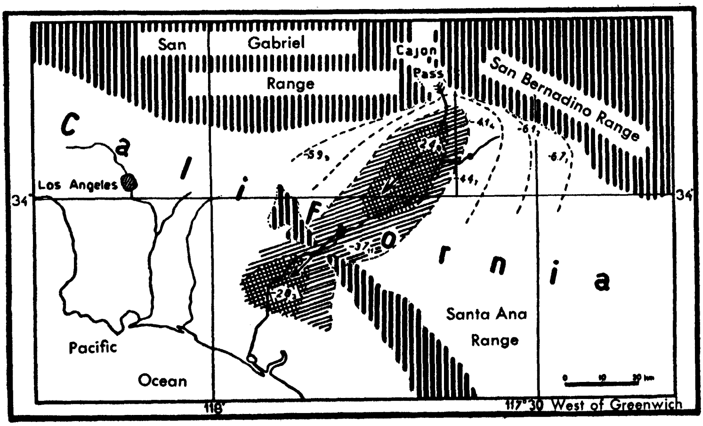

Fig. 57. Temperature distribution during the frosty night of the 19th to 20th of January 1922 in Los Angeles

was effective (see arrow), the temperatures, as indicated by darker shading, were generally higher than in the neighboring, unaffected districts. The action of the wind, here probably reinforced by foehn warming, in destroying the inversion is easily recognized.

The heating effect of the night wind depends on its velocity. The temperature change is great as we go from a calm to a steady breeze; it then decreases if the velocity increases further. Finally, there is a limit beyond which increased velocity has no more effect on temperature. This occurs when a thorough mixing of the different warm air layers has been attained.

This law can best be studied in relation to the change of temperature gradients with increasing wind velocity. At first we shall confine ourselves to observations within the province of the macroclimate. A. Ångström (46) has studied the temperature difference between the Swedish station of Wassijaure at 519 and Mt. Wassitjakko at 1372 m msl. Fig. 58 shows the result in relation to wind velocity which is chosen as abscissa. The ordinate is the temperature difference between the two stations—positive when the lower sta-

tion was the warmer. In a calm there is a strong inversion amounting to 0.6°C. At a velocity of 1½ m per sec the lower, colder air layer is so stirred up that the same night temperature is found above and below. When about 6 m per sec is reached, further increase of wind has no added effect on the temperature difference. The

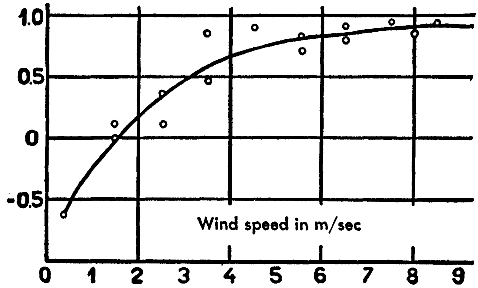

FIG. 58. Warming effect of the winds, detectable by macroclimatic temperature differences. (After A. Ångström)[1]

adiabatic value of temperature decrease with height is then practically attained.[1]

S. Siegel (*155*) from 77 separate measurements taken on four windy nights has deduced that the following relation exists in the ground air between the amount of temperature inversion within the layer from 6 to 220 cm above the ground, and the wind velocity measured at a height of 225 cm:—

Wind velocity	0.3	1	2	3	4 m per sec
Amount of inversion	3.1	2.2	1.6	1.2	0.9 °C

A series of observations over a snow surface made by A. Nyberg (*345*) is given in a later table.

We get a better insight into the relation between wind movement and temperature stratification if we measure the wind, not at one place only but consider its variation with height. For this wind gradient is in close mutual relation to the temperature gradient. A strong inversion must plainly be accompanied by a decided wind change; yet this too depends on the absolute wind velocity above.

W. D. Flower's measurements (*178*) in Egypt which have been fully described on a preceding page, give us a good idea of the interrelation of the various factors. The results from the observations

[1] In Fig. 58 the temperature gradient is shown with signs the opposite of those used elsewhere in this book.

made in the winter of 1931–1932 are shown in Fig. 59. They consist not merely of night observations, but of those made at all hours of the day.

The abscissa is the wind velocity at the upper observation point 62.6 m above the ground. The ordinate is the wind increase from

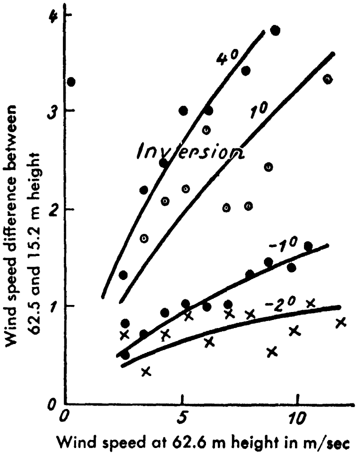

FIG. 59. Relation between the wind speed, the wind variation with altitude and the temperature gradients. (After W. D. Flower, 1937)

15.2 m to 62.6 m. The temperature gradients (negative = temperature decrease with height) are those existing between the altitudes of 16.2 and 61.0 m. They are computed for C° per 100 m. The observations plotted in Fig. 59 are grouped according to four values of this gradient. The four combined curves are marked with the corresponding value of the temperature curve.

The four curves appear to approach one another at the left of the zero point. This must be so, for if there is a calm at 63 m, it is normally quiet in the underlying air also; there is therefore no increase of velocity. If the temperature gradient is negative, then the midday decrease of temperature with height is slight (−2°C), and rate of variation of wind speed with height is small; an increased velocity does not greatly alter it, for the vertical mixing is good.

In the case of the nocturnal inversion, however, (+ 4°) the increase of velocity with height is very marked, for the cold air remains at the bottom, quiet and viscous. If the wind freshens, it only becomes noticeable at some distance above the ground. The gradient

consequently increases rapidly with increasing velocity and attains its maximum with a high wind aloft.

The normal condition of nocturnal temperature rise occasioned by the wind, we might here remark parenthetically, must not be confused with the rare, abnormal case of cold advection on a rising wind. This usually plays by no means as important a part in the weather picture as does, for instance, the outbreak over Germany of easterly wind from a Russian winter "high." This occurs on a small scale, with short-lived gusts, when for instance, air moves out of a cold hollow, or in the case of air avalanches as A. Schmauss (*414*) pointed out with reference to Alpine valleys, and as H. Scaëtta (*412*, *413*) later found in the mountains of central Africa. C. Hallenbeck (*395*) gives a good example, telling how in the Roswell fruit district (U. S. A.) the temperature suddenly fell several degrees shortly after sunrise, as some gusts of northeast wind brought in air from some of the colder surrounding country. (See the temperature curve of April 22, 1917, as there published.)

In all the discussion up to this point, the change of wind velocity within the ground air has been emphasized. We must here state a fundamental microclimatological law which has to do with the absolute value of the wind velocity.

The role played by the ground surface in the balance of radiation, of heat and of water, accounts for the temperature and humidity contrasts found within the air layer near the ground. These contrasts must, however, be caught on the spot. For this, quiet air is needed. In a storm all differences vanish; the microclimate of the ground air is suspended (with no prejudice to the fact that wind change with height is still its characteristic). Windy or stormy days are therefore unsuited to observations of the microclimate, designed to discover still unknown contrasts. To be sure, it is all the more enticing to the experienced observer to see with what tenacity the ground air layer attempts—and is able—to maintain its identity in the face of the oncoming wind.

CHAPTER 12

Optical and Acoustical Phenomena
Content of Dust, Carbon Dioxide and Emanation

W. Köppen (*247*) has fittingly remarked concerning the air layer which, aerologically considered, may be called the lowest: — "It may be analyzed into characteristic subdivisions: 1st, the layer from the ground up to a height of 1 or 1½ m, in which most of our cultivated plants grow, and in which contact with warm water or heated ground produces a mirage directed downward." Here the nature of the ground air layer is characterized by an optical phenomenon. It is therefore well — and, indeed, essential — that we do not entirely omit optics, as was done in the first edition of this book. We shall take the opportunity, at the same time, to mention other processes — acoustic, electric or radioactive — insofar as their importance in microclimatalogy is today recognized.

The great variation of temperature, water vapor and wind velocity, with height is the occasion of a great lack of homogeneity in the lowest air layer. H. Goldschmidt (*243*) beamed the light from a searchlight parallel with the ground and determined the turbidity of the atmosphere from the decrease of light intensity with distance from the searchlight. He found that the turbidity factor in this ground air was at least ten times greater than the turbidity factor of the air layer above the place of observation, which was calculated from the weakening of the solar radiation. F. H. Bielich (*239*) called the attention of flight meteorologists to the fact that visibility as determined at the ground is not of much use to a pilot in determining reliable visibility in an oblique direction. He proves it with the words, "because the most noted inequalities of the air are found in the neighborhood of the earth's surface, where forest, meadow, marsh and open water make their own peculiar little climates."

Air masses of different temperature have different densities. Where there is discontinuity of density, the light rays will be refracted toward the denser medium. If, therefore, a ray of light passes through a nonhomogeneous air mass consisting partly of warm air parcels, and partly of cold, it will deviate far from a straight path. This lack of homogeneity in the ground air is especially prevalent about midday. The heat which the ground gives off so generously

is not transported upward rapidly and smoothly enough. If we glance along a heated country road, over a sandy surface, or across a sunny field of grain, the objects in the background seem to be in constant unrest. The degree of inhomogeneity varies rapidly as small parcels of warm air detach themselves from the ground, so that a restless shimmer results. Stationary lines, such as the corners of houses, seem to be in irregular, wavy motion. This phenomenon is called "streaking" or terrestrial scintillation. The more the gaze of the observer wanders over a large area the more readily it is observed. One should not hesitate to lie down on the ground to get a better view when the phenomenon is well developed.

Fig. 60 is a photograph of this apperance obtained by L. A. Ramdas and S. L. Malurkar (*137*) in the following manner: A horizontal iron plate, 135 by 45 cm, could be heated from below. A long glass rod lay at a distance of 4 or 5 m. It was placed horizontally

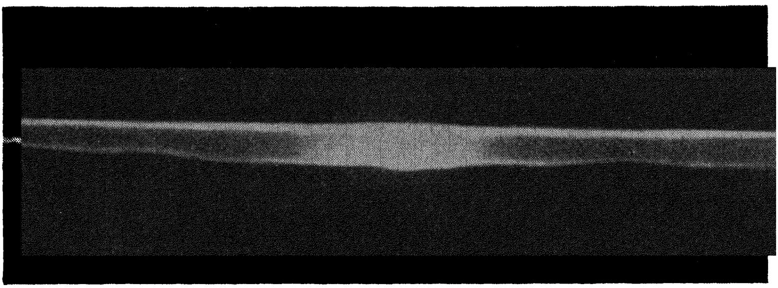

FIG. 60. Luminous line (above) with reflected image (below), that appears in form of wave motion because of "streaking"

before an open window and showed as a bright line of light. The picture of this line was taken with it just grazing the top of the iron plate. While the plate was heated, the picture shown in Fig. 60 was made, using 1/10 sec exposure. The bright upper line is the direct image of the line of light. Under this appears its reflection on the plate which has a wavy outline, the wavelength in this case amounting to 2 cm.

Another optical phenomenon, peculiar to the air near the ground, is that of air reflection downward.

In a gas, the density of which decreases with height as in the atmosphere, the visual ray between two points A and B is not a straight line but slightly curved, as shown in Fig. 61, upper left. As a consequence of this process which is called refraction of light

or simply refraction, the visual objects seem to be lifted; the observer at B sees the object A in the direction of A'. This is *superior mirage.* In the layer near the ground also the reverse process appears, such that superheated, thinner air lies under cooler, denser air. The visual ray has then the reverse curvature (Fig. 61, upper right).

If in this case the angle of incidence of the visual ray is very small so that the visual ray enters the heated layer near the ground nearly

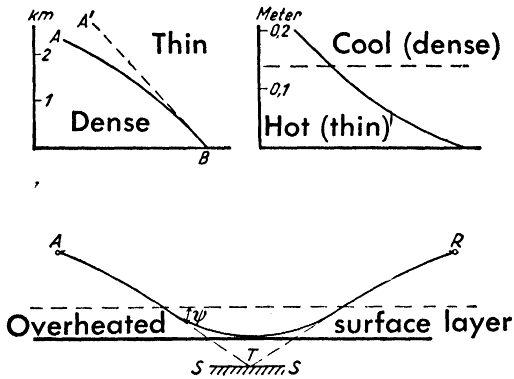

FIG. 61. Path of the rays with mirage (schematical). Mirages are to the right.

grazingly, then it may happen that the ray is curved upwards from the ground. Total reflection occurs. It is as if the visual ray (Fig. 61 bottom) were reflected from a mirror SS. Let the small angle with which the total reflection sets in be ψ. It has the order of magnitude of some minutes of arc. An observer at A sees the object, therefore, twice; the first time directly A to R, the second time indirectly reflected along ATR, and appearing below the object seen directly. It is, therefore, called *inverted or inferior mirage.* It is observed over heated roads, but mostly on shores, where, we have always a more or less free horizon and, therefore, the necessary small angle ψ. The necessary stratification of temperature is also often present on or near shore when the sand is strongly heated by the sunshine or a cool wind blows off the land and over the warmer water. How this mirage develops is amplified in Fig. 62. Let the observer's eye be at A; AF is then the eye level above the sea. AH is the direction towards the astronomical horizon, as the angle (HAF) is a right angle. The range of sight over the sea is determined by the weak curvature of the ray AKW, caused by normal refraction, which

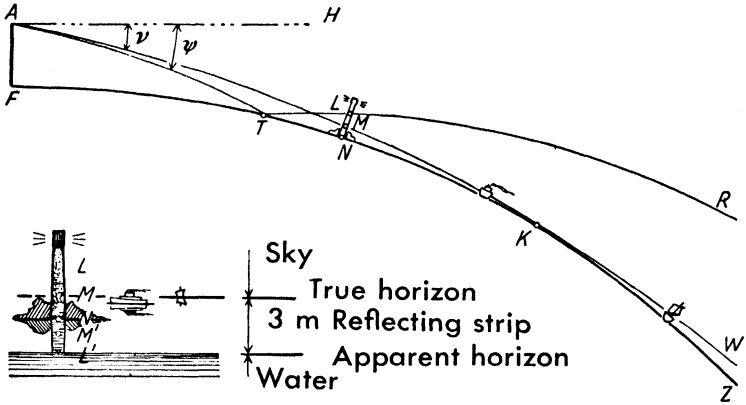

FIG. 62. Development and appearance of the inverted mirage

touches the surface of the water at K. AK is the horizontal visibility. The angle ν is the dip of the horizon. In the case of normal refraction the dip of the horizon and the range of sight are dependent upon the height of the eye level in the following way:

eye level (above sea) (m)	1	2	5	10	30	50
dip of the horizon (arc minutes)	1.8	2.5	4.0	5.6	9.7	12.6
range of sight (nautical miles)	2.1	3.0	4.7	6.6	11.4	14.8
range of sight (kilometers)	3.8	5.5	8.6	12.2	21.2	27.3

Now let us suppose that air mirage occurs. Let angle ψ, as in Fig. 61, be the greatest angle with which total reflection still occurs; then all visible rays incoming within the range of the angles ψ–ν are reflected. Let TK be the width of the reflecting strip. Since the mirror is convex in consequence of the earth's curvature the mirages appear distorted, i.e. shortened in the vertical direction. Everything in the space WKZ is invisible, everything within the space $RTKW$ is directly visible *and* miraged. The resulting pictures are represented in the sketch. The lighthouse is miraged only below L if L is the intersecting point of the visible ray RT with the lighthouse. The steamship, nearer than the horizon, is visible directly, and the sailing ship, beyond the horizon, for its upper portion, and both are miraged. The line where direct image and mirage touch each other is lifted upwards within the reflecting strip. At the distance T it coincides with the borderline between sea and (reflected)

sky, i.e. with the apparent visual horizon, at the distance K and beyond with the true sea horizon.

The theory of mirage is discussed by A. Wegener (*259a*). W. E. Schiele (257) gave a bibliography, worthy of thanks, of the most recent literature. The curves published by him, the result of all measurements hitherto made on the appearance of mirages, correspond perfectly to incoming radiation conditions. He points out in addition that the superheated air layer really responsible for the mirage is only a few centimeters thick. This explains why the phenomenon is not destroyed by the wind or by street traffic. It is very frequent over asphalt pavements around noontime and is then called a "street mirage." The mirrored image of the sky in this case gives the impression of a great puddle of water. L. A. Ramdas and S. L. Malurkar (256) have published an excellent photo of such a street mirage. W. Findeisen (*241*) using an airplane camera, took pictures of the coast at Cuxhaven from a distance of 6 to 12 km. Fig. 63 gives an example. In the upper part is a stretch of the coast at Cuxhaven shown under optically normal conditions as taken from a distance of 12.2 km. At the left appears the 30 m beacon. Below is a photograph from the same point with an inferior mirage. The mirage as outlined in Fig. 62, is easily recognized at the lighthouse as well as in the outline of the coast at the right. The dark stripes below the mirage correspond in their upper boundary to the visible horizon (the point T in Fig. 62).

In order to give an approximate idea of the value of the magnitudes involved, we quote a concrete example from A. Wegener. For a height of 10 m above sea-level (boat deck), a temperature jump of 5° at the surface and a horizon depth of $\nu = 5.6'$, the maximum angle $\psi = 12.2'$ and the breadth of the reflecting band = 12 km.

That this mirage is a phenomenon of the heated air near the ground is most apparent from the fact that it also occurs at a sunny wall. J. M. Pernter and F. M. Exner (254) published a photograph in which a boy leaning against a heated wall is visible both directly and doubly reflected. The objective of the camera in this case was only 16 cm from the wall. The line of sight therefore grazed the wall and could consequently give rise to a mirage just as though directed along the ground.

The *rainbow* occurs also as a phenomenon near the ground, namely in fountains or wherever water is sprayed. Because the artificial water drops are much larger than the largest natural drops in the case of showers the artificial rainbow is extraordinarily rich in colors. In the air layer near the water it is often seen in the spray

from the waves. What is more beautiful than to sail through the sea still heavy after the storm of the rear side of the depression when the sky is clearing and the sun, behind, is breaking through the clouds while, ahead, a rainbow appears magically again and again in spray tossed up with the dark sea as background.

The *halo* too, caused by reflection from and refraction in ice crystals, may sometimes be observed as a phenomenon near the

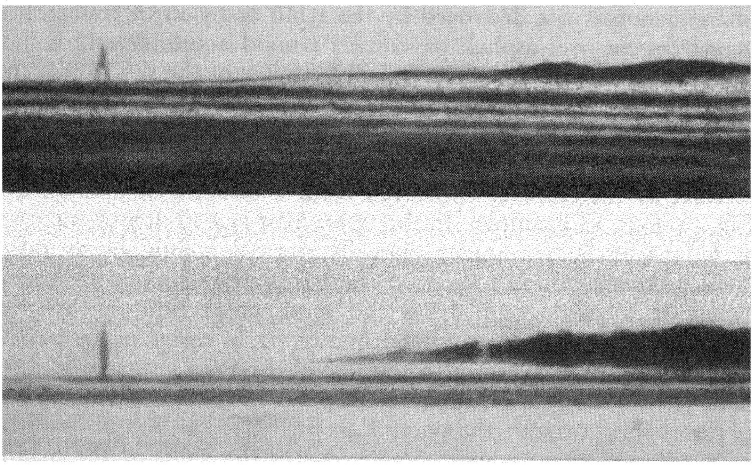

FIG. 63. Above: Coast at Cuxhaven at a distance of 12.2 km. Below: The same coast with an inverted mirage. (Photographer: W. Findeisen)

ground. H. Seilkopf (March 6, 1931) observed a halo according to W. Portig (*254a*), within the soft frost crystals shaken down from the trees by a gusty wind. Portig himself observed both parhelia, parts of the 22° halo and the upper tangential arc in an ice fog originating from evaporation of water when gas coke was extinguished in the humid, cold (−13°C) atmosphere in the region of the port of Hamburg. Seemingly, halo as well as rainbow near the ground is marked by an unusual brilliance.

From the optical phenomena we pass on to the *acoustic phenomena* within the layer near the ground.

It is generally known that the propagation of sound is dependent upon weather. The mighty thunder is very rarely heard beyond 10 miles (15 km) because of the peculiar stratification of temperature. On the other hand, heavy artillery cannonade can be heard over a

distance of some hundreds of kilometers. However, this is not always true. The propagation of sound is determined by the variation of temperature and wind with height, and probably also by the intensity of mass exchange. Therefore, the air layer near the ground influences the audibility by means of its often unusual stratification of temperature and wind. This for example was of great importance for the overwater signals formerly much used for safeguarding navigation.

When the temperature decreases quickly with height the audibility is low; the ray of sound is deflected from the surface. If, however, temperature increases quickly with height, generally at night, the sound ray, directed upwards, returns to the ground. Wind intensely increasing with height has a similar effect downwind; this also occurs mostly with inversions of temperature during the night (compare Chapter 7 and 11). In this case, the range of sound is unusually great. Some time ago, A. Schmauss drew my attention to the extraordinary audibility which is observed in streets of great cities during the night. The step of a wanderer or whispering human voices are heard at great distances. The "putt-putt" of the motor of a small fishing boat is heard even if it is far off the shore. According to a personal communication of H. Wagemann, this is the case especially in spring when warm air lies above the still cold sea and the normal temperature inversion is intensified by the weather situation.

In the polar climate, where extreme inversions occur, unusual audibility is a generally striking phenomenon. In the diary of Captain Scott (*258a*) we read of such a weather condition in the Antarctic (August 1, 1911):

> The light was especially good today; the sun was directly reflected by a single twisted iridescent cloud in the north, a brilliant, and most beautiful object. The air was still, and it was very pleasant to hear the crisp sounds of our workers abroad. The tones of voices, the swish of ski, or the clipping of an ice pick carry two or three miles on such days — more than once today we could hear the notes of some blithe singer — happily signalling the coming of the spring and the sun.

L. Aujeszky (*237*) points to two practical cases when the observer compulsorily realized the local differences of the propagation of sound, one time during the First World War in the evaluation of listening posts for the sound-measuring troops, and again in the evaluation of noise-free plots for building construction. In the first case it was a question of selecting the place where most could be

heard. The "often deceptively large differences in acoustics between places quite near together" were sought out and studied. In the second case, it was just the opposite, an attempt to find the quietest places in the neighborhood of large cities, for instance.

Local acoustics in general are not dependent entirely on the condition of the atmosphere, such as the uniform occurrence of a temperature inversion in a valley, or favorable local winds. More important are topography, vegetation and buildings. Sound waves bend around obstructions such as houses, hills and woodlots. The deep tones of artillery fire which govern the suitability of a listening post, get around such obstacles with comparative ease on account of their long wave lengths. The high-pitched, short wave, racket which annoys people, cannot do this. Sound shadows result. They must be sought out in selecting building sites which will be free from noise. L. Aujeszky has given various directions to this end. References to other literature on this subject are found in his work. B. Hrudička (777) has something on the acoustic peculiarities of city climate.

The *dust content* of the layer near the ground is determined under normal conditons by vertical temperature stratification and wind. Therefore, it has a daily variation. At the time of the nocturnal inversion and calm air the dust drops down to the lower layers. According to M. Rötschke (*256a*) the content of dust increases in the layer near the ground with beginning of the nocturnal outgoing radiation and reaches its maximum at sunrise. As soon as incoming radiation sets in and temperature increases, the dust, as a consequence of the intensified exchange, is lifted up from the air layers near the ground and, therefore, the dust content is smallest in the late afternoon. Unfortunately no observations at different heights within the layers near the ground exist so far. According to E. F. Effenberger (*240b*) the daily course of the content of condensation nuclei is reversed.

Strong wind lifts dust, sand, snow and water over the ocean (as already mentioned, page 108) and carries them into the lowest air layer. In all these cases the boundary between air and ground, snow cover or water surface respectively disappears. With the material of the surface also its properties are brought into the lower air layer. No doubt the scorching heat with sand storms of the deserts is intensified by the fact that the sand of the surface, the temperature of which is higher than the air ever reaches, transfers its heat to the air layer near the ground which carries it along.

Under such abnormal conditions, unfortunately, no measurements of the content of sand, snow or water in different heights have been made, as interesting as they might be. Only from Central Iceland I know of measurements by H. Slanar (*195*). On the occasion of strong NE winds which carry fine basaltic dust in greater quantities he fixed on a pole paper boxes the openings of which with a cross section of 25 cm^2 were directed towards the wind. During the time of July 21 to 27, the following quantities of basalt dust were accumulated there:

at the bottom	10 cm	30 cm	50 cm (height)
13 cc	2.5 cc	0.5 cc	only traces

The content of *carbon dioxide* in relation to height has been investigated by W. Kreutz (*247a*), at Giessen in the years 1939–41. Within the layer near the ground the amount of CO_2 decreased with height and increased again with further increasing height. The average values were:

height (m)	0.0	0.5	2.0	14.0
CO_2 – content (volume percent)	0.0461	0.0431	0.0417	0.0444

If all CO_2 values at 0.5, 2.0 and 14.0 m height (c_1,c_2,c_3) are correlated with the value at the ground (c_0), (according to W. Kreutz), the following relations were found by means of the method of least squares:

$$c_1 = 0.92\ c_0 + 0.2$$
$$c_2 = 0.84\ c_0 + 2.8$$
$$c_3 = 0.69\ c_0 + 12.9$$

Therefore, the content of CO_2 is composed of two components: the CO_2 emanating from the ground decreased with height as is proved by the decrease of the factor of c_0. Additionally carbon dioxide is advected originating from gases escaping industrial plants and home heating contrivances; this CO_2 comes into the air layer near the ground from above and its amount increases, therefore, with height as it is shown by the second term of the equations mentioned.

Above the ocean the CO_2 supply from below is often lacking. In the air layer near the water only a little increase of CO_2 with

height is observed. A series of measurements by K. Buch (*240x*), July 7, 1935, in the waters of New York yielded:

Height above sea (m)	0.3	1.5	4	8	30
CO_2 – content (volume per-cent)	0.0307	0.0312	0.0313	0.0314	0.0329

Several authors have been interested in the distribution of radioactive material directly above the ground. J. Priebsch (255) has made a brief summary, and I shall follow his conclusions.

Gaseous, radioactive materials in the atmosphere are derived solely from the ground. Through convection, the ground air-layer plays the same part in transmitting these emanations as it does for water vapor. It has recently been discovered that the radioactive substances are subject to decomposition. The shorter the time of disintegration, the less the height to which radioactive material can be carried by convection. Long-lived radium emanation is therefore more richly distributed at a given height above ground than is thorium B, while this again is more abundant than the very short-lived thorium emanation. Under the assumption that the exponent α has the value 1/3, we can expect the following distribution of radioactive material in the lowest air, considering the amount present at a height of 1 cm as 100:—

TABLE 19

Height above ground in cm:	1	10	100	1000	10,000
Radium Emanation	100	98	95	87	69
Thorium Emanation	100	82	50	9	0
Thorium B	100	97	91	76	49

Experiments have proved that the actual distribution is in close accord with this law.

Since radium emanation originates in the ground, the condition of the ground is of great influence on the emanation content of the ground air. We must expect considerable variation between localities. If the soil is very wet or frozen, the emanation content is small; it becomes zero when there is a snowcover of only a few centimeters thickness. When the soil is dry, it depends on the weather and the kind of soil how much emanation escapes from the pores. H. Israël-Köhler (245) has given a summarizing report

of measurements made near the soil surface to find out fluctuations in the subsoil.

F. Becker (*238*) followed the daily range of radium emanation content. At the Meteorological Institute at Frankfurt on the Main he made observations 1 m and 13 m above the ground. The results of April 4–5, 1934, are given in Fig. 64. Curve I gives the emanation content at 1 m height. It is greater in this layer near the surface than it is at 13 m (Curve II). Actually, mass exchange governs the

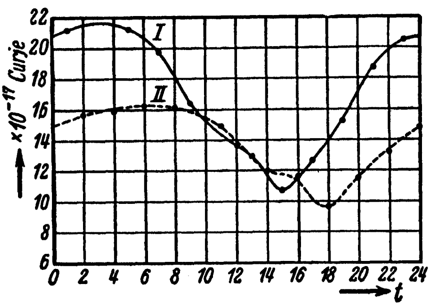

FIG. 64. Daily course of radium emanation content of the air near the ground. (After F. Becker)

content. During the calm night hours with stable temperature stratification, the difference between upper and lower stations is great. The nocturnal enrichment with emanation which takes place at this time in the neighborhood of the ground moves upward in the morning hours, somewhat weakened and with a three-hour lag. The strong midday convection irons out the difference. The minimum emanation content, however, still lags three hours behind that at the ground.

In a high Thuringian pine forest, C. Schmid-Curtius (*258*) has measured radioactive precipitation at different heights on a 20 m scaffold reaching above the tree-tops. His original work, which was done from a health-resort viewpoint, deserves study.

SECTION IV

THE INFLUENCE OF THE GROUND ITSELF ON THE CLIMATE NEAR IT

CHAPTER 13

The Temperature of the Ground Surface

All discussions up to this point in regard to the physical condition of the air layer near the ground have been under the assumption that there was no plant cover and that the ground was quite flat. Both these assumptions still hold in what follows.

We wish now to focus our attention on the influence of the earth's surface on conditions in the ground air. Hitherto we have assumed that all observations have been made over a uniform, solid ground — fine sand, for instance. Although we could not avoid mentioning now and then the influence which the kind of soil exerted on the lower air, it is only at this point that such effects are to be thoroughly examined.

In nature we find three different kinds of surface on the earth — land, water and snow. Among these, land shows the greatest variability, even without considering the varied vegetation which may cover it. There is no end to the varieties of soil; its variation with depth is different in different places. The condition of the soil is affected by varied cultivation. Moreover, changes of humidity result in different ground conditions from time to time.

While, in the case of land, it is only the uppermost layer which receives and gives off radiation — in fact merely the boundary surface adjacent to the atmosphere, a different condition exists in regard to water and snow. Solar radiation can penetrate both water and snow and the heat exchange between earth and air is not merely a surface matter, but has to do with a vertical distribution to a considerable depth. Both water and snow vary with depth. The water in a shallow puddle has an influence on the adjacent air which is quite different from that exerted by deep water. Standing water acts differently from running water that carries its heat relationships with it. As for a snow cover, it is its age, especially, which markedly affects the physical condition of the surface and of the air adjacent to it.

Conditions over water and over snow are considered in Chapter 15 and 16. Nevertheless, for the sake of a proper perspective, we must interject a few pertinent remarks here and now. We shall devote the present chapter to the processes at the surface of the land, and shall begin by investigating how the surface affects radiation.

By "reflection number," "reflectivity" or "albedo" is understood the ratio of reflected radiation to the insolation; it is usually expressed as a percentage. A reflection number of 0.4 (or 40%) indicates that the ground reflects 40%, and absorbs 60%, of the radiation which strikes it. According to Kirchhoff's law, the ratio of emissivity to absorptivity is constant for a given wave length and temperature. If, therefore, a body has low absorptivity and high reflectivity for a certain wave length band, it has low emissivity in the same range of wave lengths.

Three spectral bands should be differentiated. 1. The ultraviolet, with wave lengths below 0.36 μ; 2. the visible spectrum, with wave lengths from 0.36 to 0.76 μ, and finally; 3. the long wave (infrared) from 0.76 to about 100 μ. We shall begin with the ultraviolet.

According to the measurements of P. Götz (*334*) and F. Lauscher and O. Eckel (*341*), the reflection number of a snow cover in the ultraviolet is from 80 to 85%. All other surfaces have only a small reflectivity in the ultraviolet. W. Hausmann and F. M. Kuen (*273*) 22 to 25% for stone (gravel, granite, chalk), and 6% for garden soil. K. Büttner and E. Sutter (*307*) observed 17% on dry dune sand, and 2% in dune heath. H. Voigts (*283*) estimated, from comparative measurements along the Bay of Lübeck, that on clear July days, the reflection of the sandy beach caused an 8 to 9% increase in the ultraviolet.

Most of our observations are for the visible range of the spectrum, those of A. Ångström (260) and K. Büttner (264) for example. J. Bartels (*261*) made a compilation in 1930. The following figures, selected from all the measurements, will serve at least as a rough table of comparative values.

Reflection Number (Albedo) of Various Surfaces for the Visible Portion of the Spectrum

Fresh snow cover	80–85%
Cloud surface	60–90
Older snow cover	42–70
Fields, meadows, tilled soil	15–30
Heath and Sand	10–25
Forests	5–18
Surface of the sea	8–10

On later pages we shall give further data on the albedo of snow and also that of water, particularly as to mirages when the sun is low.

If dry sand is moistened, it appears darker. This is an indication that the albedo of moist surfaces is less than that of dry ones.

A. Ångström (*260*) observed that a certain gray sand had an albedo of 18% when dry, but 9% when moist. For a high, brightly colored grass carpet, the corresponding figures were 32% and 20%. K. Büttner and E. Sutter (*307*) determined the albedo of dune sand at Amrum:

TABLE 20

	For the total radiation (0.5–3.0 μ)	For ultraviolet radiation (0.3 μ)
In dry condition	37%	17%
In moist condition	24%	9%

We shall mention this again in connection with Fig. 73.

Ångström has also given an explanation of this fact: When the particles of the soil or plant surface are covered with a film of water, light rays can enter the water film in all directions, but the only rays which can emerge are those which can reach the surface of the water film within the limiting angle of total reflection. The water film therefore retains part of the radiation.

For the infrared portion of the spectrum, we have the observations of G. Falckenberg (*269*). Most surfaces are practically "black bodies" for this spectral range, i.e. they absorb almost all radiation which strikes them. For instance, Falckenberg's observations show:—

for light colored sand, an albedo of	11%
for light gray limestone, an albedo of	8–9%
for coarse gravel, an albedo of	8–9%
for clods of earth with sod, an albedo of	2%
for snow, an albedo of	0.5%

Snow, in particular, devours practically all radiation. Hence this paradox of Falckenberg: "Fresh-fallen snow is the 'blackest body' we know." An exception seems to be a living vegetation cover, which will be treated in Chapter 26.

In regard to the body surfaces of animals we may say that F. Rücker (277) found a minimum of the preponderantly diffuse reflection between 1.9 and 2.2 μ for beetles, between 2.6 and 3.0 μ for butterflies and between 1.7 and 2.2 μ for snailshells. For example, for a butterfly's wing (forewing of Pieris brassicae) he found:—

for wave length (μ)	1.1	1.5	1.9	2.2	2.6	3.0	3.5
an albedo (%)	69	70	61	55	31	27	35

The different reactions of various soil types to radiation is noticeable in the heat economy of the air near the ground. A soil surface with a high index of reflection heats up by day much less than one with high power of absorption. For example, we find very high temperatures over dark moor soils by day, and this is responsible for the extraordinary demands upon plants in the frost-endangered mucklands.

It has already been mentioned how important it is in regard to the whole heat economy on the earth's surface, to know the temperature of the surface itself. It is best defined as the "temperature of the boundary surface between earth and air." To measure it accurately is a matter of considerable difficulty.

All earlier measurements made with mercury thermometers are useless. On the one hand the temperature "*on* the earth's surface" was measured—which meant placing the thermometer flat on the ground. In this case the measurements obtained were those of the lowest airlayer, influenced by radiation and dependent on the construction of the particular thermometer. Measurements "*in* the surface" were carried out by placing the thermometer within the soil but covered by only a very thin layer. Such a thin cover is easily carried off or heaped up by wind or rain. But even when there is a careful observer to watch the exposure of the thermometer, it is only the temperature close beneath the surface of the soil which is obtained.

By means of thermocouples, made so tiny that their radiation errors are vanishingly small, the surface temperature can be obtained electrically with quite satisfactory accuracy. Great care must be exercised to make sure that the thermo elements are in closest contact with the surface. Wilh. Schmidt (279) used inserted glass tubes to determine the temperatures of the surface, the air layer above, and the earth layer beneath, by touching the tube wall with the thermocouple.

It is an intriguing idea to measure the surface temperature by day or night, not directly at the surface but indirectly as a tempera-

ture boundary. It is possible to do this by observing the gradient of temperature in the ground or in the air in very close contact with the ground and then extrapolating for the temperature of the surface itself. A. Nyberg (*345*), for example, did this. Or we can determine the temperature of the surface from its temperature radiation. G. Falckenberg (*270*) has made and used apparatus of this nature. K. Wegener (*75*) and H. Trojer (*74, 76*) used a parabolic mirror at whose focus the radiant heat was concentrated.

In India K. R. Ramanthan (*274*) followed the suggestion of G. Chatterji by inserting a mercury thermometer in a well-conducting copper plate of 1.5 sq cm area. The thermometer was as close as possible to the under surface of the plate. By means of a sheet of felt which rested upon the plate, insulating it from heat and also serving as a handle, the copper plate could be moved about here and there over the heated ground. This "flatiron" method gives a mean value over a rather large area and is at any rate the best way to use a mercury thermometer in measuring ground surface temperatures. Mention should here be made of the original method by means of which an English biologist in the Syrian desert was able, without dismounting from his horse, to determine approximately the temperature of the ground. He carried with him a great quantity of wax balls whose melting points varied by regular steps. Thus he could measure the surface temperature to within the difference between two successive melting points.

It is on the surface of the ground that the highest midday temperatures are found — unexceeded in the neighboring air. Fig. 65 represents a temperature measurement made by G. S. Eaton (*268*) in Riverside, Illinois on Aug. 7, 1918. It is an interesting example since asphalt pavements play an important part in the life of the modern city-dweller. The dot and dash curve gives the air temperature as measured in the shade, 10 m to one side of the street. It shows the normal march of temperature with a maximum at about 3 P.M. Considerably higher are the air temperatures at 120 and 30 cm above the street, while the surface of the street at noon is about 20° warmer than the air layer a few decimeters higher.

Notice the time of the temperature maxima as indicated on the chart! The maximum on the surface follows the daily period of solar radiation more closely than does that of the air temperature, and is therefore earlier than that of the air. Most striking, however, is the broad maximum in the air near the ground, which tends to persist till evening. The reason for this is probably that the asphalt pavement stores up so much heat around midday that it continues to

give off heat to the air lying above it, during the afternoon. In Fig. 65 the street is 8° warmer than the air 30 cm above the ground at 4 P.M., and is still 5° warmer at 6 P.M.

The high temperatures existing in the solid pavement result in phenomena which A. Schmauss (*278*) has described. The ground under the concrete is almost entirely sealed off from atmospheric breathing. "The result can be seen in bulges and bubbles of the asphalt which is evidently subjected to a gas pressure from below.

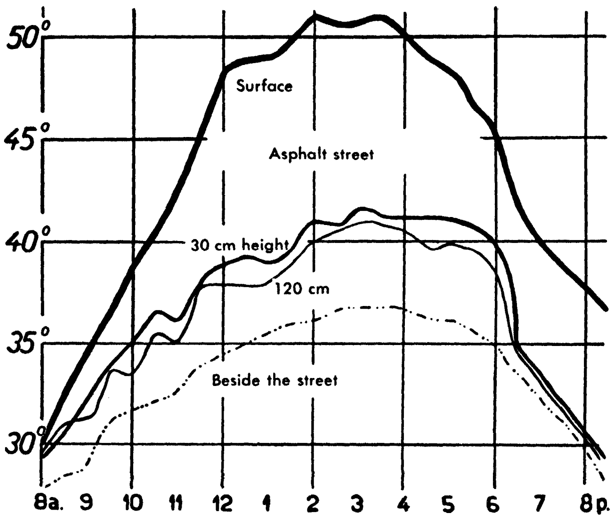

FIG. 65. Temperatures above an asphalt street. (After G. S. Eaton)

This condition occurs particularly where there are little holes in the material with rounded edges which must have been caused by escaping gas and which look like the "eyes" that occasionally crack out on a viscous liquid left standing over a burner. But in that case the flaws close up again, while in asphalt they are permanent."

The midday temperatures of more than 50°, which are indicated in Fig. 65, are by no means the highest experienced in our climate. According to a recent compilation by Br. Huber (*514*), surface temperatures of 70°C and even more have been repeatedly observed. On southern exposures in our climate temperatures up to 80°C can be expected under favorable conditions. A reference to the harmful effect of this on young plants is made in Chapter 17. The following

example shows how surface temperatures may work out in polar climates.

In his report on the German Antarctic Expedition of 1938–39, A. Ritscher (*276*) states that in New Swabia Land, 100 nautical miles inland from the edge of shelf ice a number of pools were discovered between dark red rounded peaks in the midst of the glacial ice. "Our first impression, that the evident melting process was attributable to heat from within — vulcanism, in other words — seems to have changed to the hypothesis that it is the consequence of heat storage due to intensive insolation, with which the dark reddish brown color of the surrounding rock would best agree."

"Black bulb" thermometers are ordinarily used in measuring radiation. These are mercury thermometers whose bulbs have been blackened in order to absorb as much as possible of the incident radiation. The bulb is surrounded by a second glass bulb; the intervening space is evacuated so that the thermometer can transmit no heat to the air.

There is a common impression that the surface of the ground, which of course gives off heat to the air, corresponds in the highest degree to the temperature of a black bulb thermometer exposed to the same conditions. A. F. Dufton and H. E. Beckett (*267*) have shown that this is a false opinion. In the case of the black bulb thermometer there is an equilibrium set up between the heat intake through insolation and the heat output through radiation to the surrounding glass bulb. In contrast to the black bulb thermometer, a natural surface is subject to heat loss by conduction and convection. A plane surface, however, can radiate heat only toward half a hemisphere, i.e. upward, while the blackened bulb can radiate to all directions. If the natural ground surface is concave, the storage of heat is still greater. A hindering of convection and a poorly conducting soil have a similar effect. Dufton and Beckett present the following data: — Air temperature, 20.6°C; Black bulb thermometer, 56.1°C; Surface of a tar-paper roof over a heat-insulating base, 65.5°C. One more extreme instance: If you construct a well insulated box with blackened walls, and cover the box with a pane of clear glass, you can cook a blackened egg in it — reaching a temperature of 120°C. So the black bulb thermometer does not indicate the extremes of surface temperature which are possible under peculiar local conditions in the microclimate.

Many attempts have been made to determine how the nature of the surface affects ground temperatures. Thus, for example, E. Wollny (*285*) colored three different kinds of soil partly black and

partly white and studied the temperature range beneath the surface. Fig. 66 shows a recent attempt of the same sort, made by L. A. Ramdas and R. K. Dravid (300) under the strong sun of India. The left half represents the temperature range during the 40 days' experiment, on the same test surface; the right half, an untreated control surface. Both surfaces had "black cotton bases." Five days after the beginning of the measurements (Point *A*), a very thin layer of white powdered lime was dusted over the test surface. This caused the isotherms to turn suddenly upward, continuing to rise

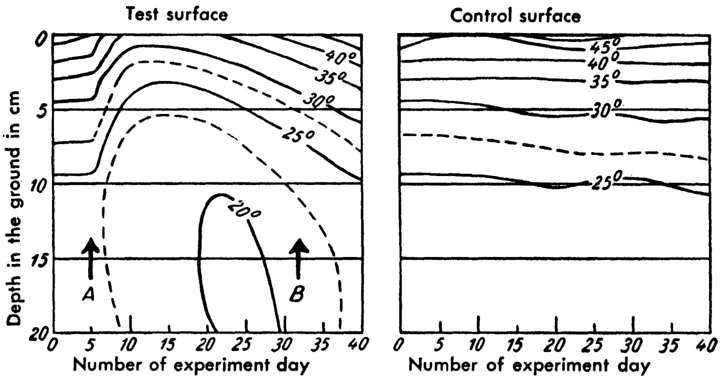

FIG. 66. Change of the ground temperature owing to scattering (A) of white lime powder. (After L. A. Ramdas and R. K. Dravid)

for nearly 10 days until the change is complete. At the ground it is then about 15° cooler than at the surface of the black soil. The surface effect is felt to a depth of at least 10 cm. At Point *B* the powdered lime was removed. It had already weakened in effect by reason of wind and humidity, but after its complete removal it was still 1 to 2 weeks before conditions were the same on the test surface as on the control surface.

C. Dorno (266) has investigated the effect of painting on the temperature of wood. For this purpose he placed four small, cylindrical wooden blocks, 3 cm high by 2½ cm in diameter, in the sun on a south-facing balcony at Davos. Thermometers were inserted in mercury-filled holes in the wood. He found that the effective radiation amounting to one gram-calorie caused the temperature of the wood to rise above that of its surroundings by the following amounts for the various colors:—

White lead paint	10.8°C
Rosepaint (zinc white with dammar lacquer)	11.0°C
Yellow ochre paint	14.8°C
Red oil paint	15.7°C
Lamp black	16.9°C

K. Schropp (*281*) carried out a series of measurements for technical finishes. The surfaces in question were placed on an insulating cork plate, 5 cm thick, while the temperatures were measured in sunshine and quiet air by means of a thermocouple. He found that, under similar daytime conditions, black paper or black enamel attained a temperature of from 45° to 55°C; white surfaces, 15° to 20°C; while polished aluminum foil showed only 15°C. By night all the surfaces had temperatures 2 to 4° lower than the air.

Railroad tracks heat up strongly in sunshine. The only known measurements are those of K. R. Ramanathan (*274*) in India. In Agra he placed a rail 1.5 m long on broken stone 10 cm above the ground. A hole, drilled vertically 25 mm into the rail was half-filled with mercury. In this the thermometer was inserted. The following table gives an abstract of several average and absolute monthly extremes in degrees centigrade for both the railroad rail and an air temperature control measured within a Stevenson shelter.

TABLE 21

	Maxima				Minima			
	Mean		Absolute		Mean		Absolute	
Month	Air	Railroad track	Air	Railroad track	Air	Railroad track	Air	Railroad track
May, 1927	41.4	56.1	45.1	59.8	25.6	23.2	23.1	20.2
June	41.0	54.6	44.3	61.1	27.8	26.2	20.9	17.3
August	31.5	47.7	36.6	54.4	25.2	24.7	22.5	21.9
September	34.0	49.6	37.7	56.5	22.5	21.7	19.4	18.1
November	26.6	39.6	31.7	47.4	11.4	9.5	5.8	3.2
January, 1928	21.6	34.2	25.0	40.9	7.1	5.2	2.7	1.5

In Geisenheim on the Rhine, H. Schanderl and N. Weger (*277a*) experimented in 1938–39 with a 3 m trellis wall of light brown quartzite facing toward the southwest. It was partly painted black and white. In front of it tomatoes were planted, whose growth and yield were measured. The true air temperature was observed by means of a platinum wire thermometer, while the counter-radiation

of the wall was obtained with a black bulb resistance thermometer. At a distance of 10 cm from the wall the difference between the air and plant temperatures in front of the three different parts of the wall was not very great but that between the amounts of counter radiation was. If we consider the total radiation of the black wall as 100, that of the natural colored wall on the sunny 19th of June 1940 was 110, while that of the white wall was 156. In the short wave part of the spectrum the differences were still greater.

At first the tomatoes in front of the black wall grew considerably faster; their yield, however, was less. The amount of radiation, in conjunction with the overpowering long wave counter radiation stimulated the plants here to purely vegetative growth. The greater amount of radiation (short wave, especially) in front of the white section of the wall retarded growth in height but stimulated productivity. The greater yield of tomatoes in front of the white wall justified the cost of painting.

Mention should be made here of the movement of the ground surface by frost. In the spring it plays an important part in agriculture at times ("heaving"). R. Fleischmann (*271*, *272*) has described a simple arrangement by means of which the vertical movement of the ground can be easily measured, and has himself carried on numerous observations. Under "Heaving" he writes as follows: "The action of frost on water particles in the pores of the soil results in an increase of their volume; thawing, on the other hand, occasions a sinking of the surface. The greater the difference between the degrees of frost at 2 P.M. and at 7 A.M. on the following day, the greater the amount of ground frozen, and the deeper the scene of this action lies beneath the surface, the greater the heaving effect." It appears that tearing of roots in the soil, with consequent damage to agriculture, begins when the heaving of the soil amounts to about 15 mm. To give an idea of the amount of heaving which ordinarily takes place, the following figures are taken from R. Fleischmann's findings for the years 1931 through 1935:—

Heaving Movement	0–5	5–10	10–15	15–20	20–25 mm
Number of cases					
1931–1935	57	38	4	3	2

Concerning the process of soil respiration, which we shall not discuss here, the reader is referred to the recent work of M. Diem (*265*) and W. Schmidt and P. Lehmann (*280*).

CHAPTER 14

The Influence of the Type and Condition of the Soil

In the preceding chapter we treated only the surface of the ground, its characteristics and temperature relationships. The temperatures in the ground below the surface were considered in general in Chapter 3. There we mentioned the effect of the heat conductivity of different kinds of ground.

The influence of the kind of soil and its condition upon the microclimate is, however, so great that we feel we should deal with it in the present chapter in more detail. The following computation by H. Philipps (*68a*) (from his "Theory of heat radiation near the ground") will well show this influence. Under the assumption that at sunset the temperature is 11.5°C and the water vapor pressure 5.8 mm he finds the following decreases of temperature of the ground in the course of 10 night hours for different kinds of soil in dependence on the intensity of mass exchange:

TABLE 22

Kind of Soil	Cooling of ground (°C) within 10 hours with a coefficient of exchange $A = 0.01$	$A = 0.70$
Granite	7.6	7.0
Loamy Sand	10.9	9.6
Peaty Soil	12.5	10.9
Dry Sand	13.6	11.7
Wet Sand	16.2	13.5

When the exchange is greater more heat is supplied from the air layers near the ground; the decrease of temperature of the surface is, consequently, smaller. What is so significant with these numbers is the dominating influence of the kind of soil. A first glance at the nocturnal thermal economy in Fig. 7 (page 22) explains this fact, The supplementary heat supply from below is dependent upon the kind of soil, the amount of evaporation (water content of the ground) and (indirectly through the surface temperature) also the effective outgoing radiation. When taking into consideration the width of the arrows of Fig. 7, we see that the nocturnal thermal economy is

— in principle — already determined by the three elements already mentioned. The kind of soil and the conditions of the ground are, therefore, more important for the danger of night-frost than the more or less intensive exchange within the air layers near the ground.

The temperatures of the ground consequently govern the climate near the ground to the greatest extent; this is valid not only for the night, as in the above mentioned example, but for any time. W. Kreutz and M. Rohweder (*297*) have proved this close relation between the temperature of the ground and that of the air, calculating correlation factors. In the following, we deal more in detail with the soil conditions and investigate, first, the influence of the soil, i.e. sand, clay, humus, etc.; then, we discuss the influence of the ground conditions, its state of cultivation, its water content, etc.

From the 10th through the 12th of August, 1893, Th. Homén (*82*) carried on a series of clear-weather temperature observations in Finland, both on and above three different kinds of soil. These old experiments, which were far in advance of our knowledge in those days and which have not been surpassed since, will serve as our first example of the influence of the nature of the soil on the temperature cycle. Fig. 67 gives graphically the highest and the lowest daily temperature for the three days mentioned.

For granite rock (dotted line) the maximum of 35° occurs (as is to be expected) on the rock surface; the temperature falls rapidly in the air above. The coincident maximum air temperature at a height of 2 m, which is only somewhat over 23°, is indicated by a small double circle. Going into the rock from the surface, the temperature at first decreases rapidly, then more slowly. By night its course is reversed. Within the rock the temperature increases with depth. The minimum occurs, not on the rock surface but at the level of the surrounding grass, which cools off more than the rock does.

The minimum air temperature of not quite 10°C at 2 m height, which is indicated by a small double circle shows, abnormally, a still lower temperature than the rock surface. The air temperature is not measured over each kind of soil separately, but is observed once for the three places. The rock, with its good heat storage, however, has relatively high temperatures. The two dotted curves consequently lie well to the right in Fig. 67; the maximum and minimum curves are widely separated and do not meet, even at a depth of 60 cm. This is an indication that daily heating penetrates deeply into the rock. The result is that even by night a good deal of heat is passed out from within, thus accounting for the high level of temperature in the rock at night — higher than that of the air. If one

passes close to a stone-wall in the evening or near a house which stands by itself, he can feel directly the return of the stored up day's heat as it is being given back to the adjacent air.

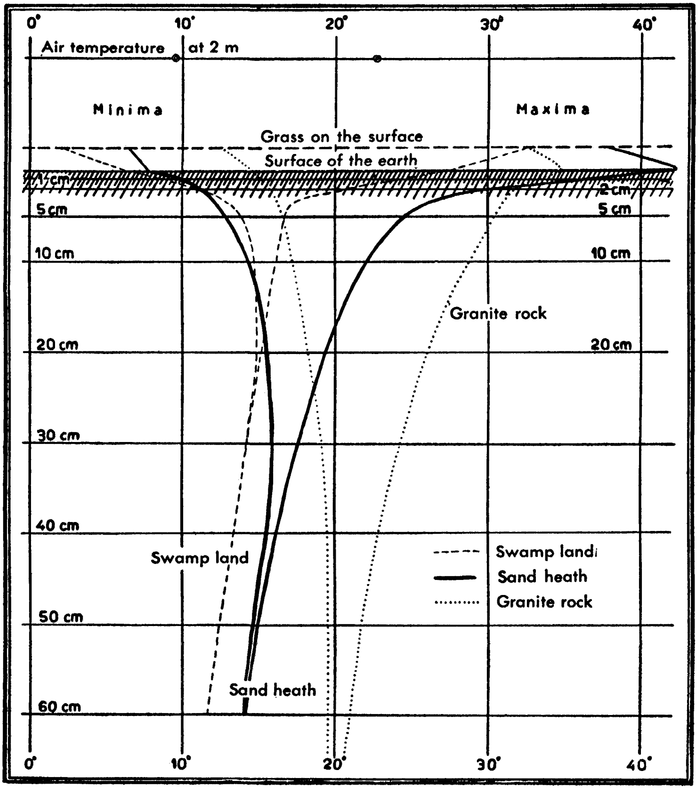

FIG. 67. Temperature maxima and minima in three different kinds of ground. (After Th. Homén)

Sandy soil (solid lines) heats up to an extraordinary degree in its uppermost layer, more so, even, than does granite. But the temperature decreases very rapidly both upward and downward. Like granite, it is a dry soil, but has much lower heat conductivity on account of the air spaces between the sand grains. The day's heat does not penetrate so deeply as in granite; at 60 cm depth there is practically no evidence of daily fluctuation.

How peculiar is the behavior of the damp moor! The broken-

line curves lie at the left in Fig. 67—in the cold region. To be sure the maximum at the surface (which is here the surface of the grass) is quite far to the right. The temperature drop within the soil, however, is very abrupt; even at a depth of only 5 cm the daily range, on account of the low heat conductivity, is as insignificant as at a depth of 45 cm in granite. At 25 cm it has disappeared entirely. During the night the moorland shows the lowest temperature of any; again the minimum occurs at the top of the short grass. The fact that the curves for the interior of the earth slope in general from upper right to lower left is occasioned by the observations being made during a time of warming up—fair weather after cloudy days; the interior temperature lags behind this warming process.

Because of the dark color (see p. 134) the daytime temperatures on the peaty soil are comparatively much higher in the climate of Germany which is richer in radiation, than could be expected according to these observations in Finland. The extreme daily variation of temperature and the low thermal conductivity are properties of the moor *despite* its high water content. Therefore, drainage of the moors intensified generally the microclimatic disadvantages, especially the frost danger. It is diminished most effectively by sanding the moors because in this way the nature of the surface layer of soil, which chiefly influences the adjacent air layer, is changed. At Emslandmoor, W. Kreutz (*296b*) studied the daily variation of temperature over experimental areas that were covered with sand, 5 cm, 10 cm, and 15 cm deep and could prove that the thermal conductivity and the storage of heat in the ground was increased with the depth of the sand layer. Also, the open water surfaces of the trenches in the moor moderate the frost, at least for a distance of a few dekameters.

Another example of soil effect is given by N. K. Johnson and E. L. Davies (*292*). In 1925 they made temperature observations in six different kinds of soil on Salisbury Plain in England. The various soils were in boxes 1 meter square, filled to a depth of 15 cm. A maximum and minimum thermometer were each inserted in a brass tube, 1 cm in diameter and 10 cm long, and placed 1 cm beneath the surface of each type of soil. The following table gives the monthly temperature range in C° for June and January.

June typifies summer conditions. By far the greatest temperature range is shown by the tar-macadam which we have already identified as the extreme, artificial ground cover. Next comes sand, then earth, and later the grass-covered soil, in agreement with Homén's results.

TABLE 23

MONTHLY RANGE OF TEMPERATURE (°C)

	June 1925	January 1925
Tar — Macadam	32.6	6.8
Sand	25.9	5.4
Earth	25.0	5.4
Gravel	21.1	5.7
Grassy ground	16.0	3.3
Clay soil	11.5	5.0
For comparison: air temperature at 1.2 m (Stevenson shelter)	14.2	6.6

Gravel, on account of the many poorly-conducting air-filled spaces, does not have the characteristics of rock, which we learned from Fig. 67. Particularly low is the range for the moist clay soil. The simultaneous range of the air-temperature is appended in the last line of the table. It is slight in comparison with that of the soils, as we might expect from our knowledge of the temperature range in the lower air as compared with that in the ground.

In January, however, (that is, in winter) the temperature range of the air is almost as great as that of the macadam. While in summer the air is in next to the last place, in winter it is next to the first. In summer, radiation and the earth temperature governed by it, determine the air temperature near the ground. In winter, however, when radiation is weak (particularly in the cloudy maritime climate of England) the influence of the ground diminishes. The air temperature is governed by the change of air masses and consequently shows a relatively large monthly range.

Recently W. Kreutz (*296c*) has investigated the annual course of temperature in loam, sand, and humus at the agrometeorological research station at Giessen. He published the annual temperature variation on the average of the years 1939–1941, based on 10-days means for the depths 5, 10, 20, 50 and 100 cm. The ideal temperature variation derived from these observations resulted in the temperatures shown in Table 24. The values for the surface (not observed) are extrapolated.

Fig. 68 gives, according to Wilhelm Schmidt (*113*), a picture of the different fractions of the total heat which can be utilized by the ground and the air, respectively. The latter are shaded in the cut. Ground types which show a large amount of white, tend toward a mild microclimate; those types showing considerable shading, toward a microclimate of extremes.

TABLE 24

Depth cm	Average Annual Temperature (°C) Loam	Sand	Humus	Annual Range of Temperature (°C) Loam	Sand	Humus
0	9.1	9.3	10.1	20.0	21.6	23.0
10	9.3	9.5	10.3	19.6	20.8	22.0
20	9.5	9.7	10.4	18.8	19.8	21.0
50	9.9	10.3	10.8	17.0	17.4	18.2
100	10.7	11.3	11.3	14.2	14.2	14.4

In top place is the ocean. For reasons which will be explained in the following chapter, water retains almost all the heat radiated to it. Consequently, there is practically no daily range of temperature in

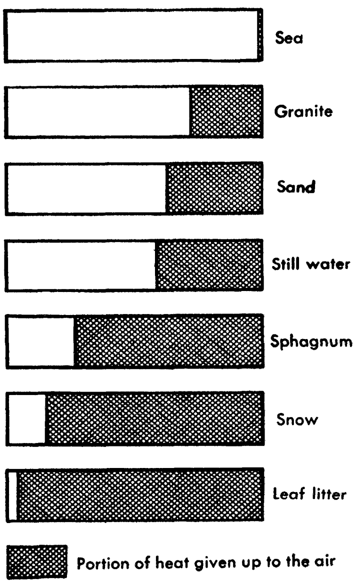

FIG. 68. How the different kinds of ground utilize incident heat radiation

the air near water. Over the ocean the daily fluctuation of air temperature is not over ½ °C. In second place is granite, which is known to us, from Homén's investigations, for its favorable heat balance. Close behind sand, which stands in third place, comes quiet water. By this is understood water which is not being in any way stirred

up. This condition is met by shallow pools on land. Again it is Wilhelm Schmidt (*327*) who has been able to prove these theoretically stated facts by practical measurements. When a person is sailing over a land-locked bay on a hot summer midday, he can experience this very impressively in the oppressive, sultry heat which prevails in the air just above the water.

In next place, according to Fig. 68, comes the sphagnum bog, which has an important, and indeed unfavorable, influence on temperature conditions of the moorland. In next to the last place is snow. The extreme temperature range in the air above snow is known from the very low winter temperatures which occur as soon as the ground is insulated by a snow-cover. (More of this in Chapter 16.)

For many practical questions it is of great significance that the decayed vegetation which covers the soil, leaf litter, for example, has an even lower heat conductivity than snow. Over such a cover therefore the temperature range within the province of the microclimate is greater than over snow.

F. Firbas (*288*) has shown, through a long series of microclimatic temperature measurements in oak and beech forests, that the rapid heating of the sun-irradiated leaf litter enables the spring vegetation in these forests — such as anemones, hepaticas, etc. — to produce their flowers before the leaf buds of the beeches and oaks. In the early days of May he found temperatures up to 43° within the leaf-litter. The disadvantage of strong outgoing radiation is in this case lessened by the fact that even the leafless trees form an effective screen against outgoing radiation.

The foregoing is however a particularly favorable instance. Normally, poor heat conductivity is a great disadvantage, especially in forestry. When a newly laid out culture of grass and weeds has grown up and dies down in the autumn, increasing the ground cover by all its organic material, such a culture becomes a center of frost, for the exceptionally high noon temperatures, which entice the plants to push upwards, are offset by exceptionally low night temperatures. In a laboratory district of the Forestry College at Eberswalde, R. Geiger and G. Fritzsche (*290*) have recently furnished numerical proof of this.

In a weed-covered, frost-damaged pine plantation, one part of the ground had been plowed deeply as for a tilled crop. This deep cultivation had torn apart the dead, poorly conducting surface layer of the soil and thoroughly mingled it with the more highly mineralized subsoil. In 1937 and in the late winter of 1939 parts of the

planting were treated in this manner. In the spring and summer of 1939 the nocturnal temperature minima were measured at a height of 10 cm above these two areas and also above the unplowed surface: Four observation stations situated at exactly the same altitude afforded the data for the next table.

In all the figures the influence of the kind of soil is clearly and constantly in evidence. The alteration of the soil through deep tillage affected the heat economy of the adjacent air favorably and lessened the frost damage to the vegetation growing there.

TABLE 25

Type of Ground	Late season frost nights, 1939 13/14 May	29/30 May	10/11 June	Mean of 30 cold nights	Number of frost nights	Last late frost
Weedy frost area in a shallow bowl	−3.5	−8.1	−4.1	−0.6	17	12 July
Weedy cultivated plain	−1.6	−6.5	−3.7	+0.2	15	28 June
Soil deeply plowed in 1937	−0.3	−3.9	−1.0	+3.3	9	15 June
Soil deeply plowed in 1939	+0.2	−3.4	+0.5	+4.0	6	15 June

The second deep-tillage proved more effective than the former. The land plowed up in 1937 settled in time and began, as could be seen, to cover the consolidated surface with weeds again. Here there is, on the one hand, a further proof that it is actually the disturbance of the soil which is responsible for the change in the night temperatures, and, on the other hand, a practical hint that deep tillage loses its frost-protecting properties to the extent that the vegetation growing thereon becomes grosser and more frost-hardened.

The different thermal conductivity of the kinds of soil finds its expression by the manner in which the *winterly frost* penetrates the ground. At the experiment station of the agrometeorological research station at Giessen, W. Kreutz (*296a*) made the observations in the hard winter 1939/40 shown in Table 26.

In Fig. 14 (p. 33) the trend of the 0°C — isotherm indicates the range of winter frost in the ground as to space and time. Similarly, W. Kreutz gave many representations of the frost phenomenon for many kinds of soil and for a number of stations for the winter 1939/40 in his paper.

TABLE 26

Kind of Soil	Depth of Frost cm	Speed of Penetration cm/day	Late frost in spring	Lowest temperature in the depth (cm) 10	20	50	100
Humus	32	0.6	Mar. 22	−2.0	−0.5	0.4	3.0
Loamy sand .	40	1.1	Mar. 7	−5.2	−3.3	1.1	1.8
Loam	52	1.1	Mar. 16	−9.6	−4.6	−0.1	1.0
Sand	52	1.7	Feb. 28	−9.6	−7.0	−0.1	2.1
Basalt dust .	67	2.0	Feb. 25	−12.0	−8.1	−1.2	2.1

Along with the *kind* of soil we must consider its *condition.*

In the preceding example, one kind of soil was changed to another by plowing; i.e. a two-layer soil, (a layer of humus-bearing top soil over a mineral-bearing subsoil) being changed into a homogeneous prevailingly mineral soil. If, however, we confine our attention to one kind of soil, the effect of plowing is to make it looser, so that it contains more air. Since the air conducts heat much more poorly than any kind of soil, tillage results in poorer heat economy.

This is the explanation, for instance, of K. Bender's observation (*808*) when he writes: "I shall always remember how, after a frosty night, the plants in a certain potato field which had been weeded the day before were all frozen, while those in a piece which, fortunately in this case, had not been worked on, escaped with no damage." Similar observations are often made. Wilhelm Schmidt (*302*) carried out comparative temperature measurements in an unplanted, and unplowed, field. The temperatures on the 23–24th of August, 1924 were as follows:

TABLE 27

Time of day	Early, about 5 A.M.		Afternoon 3 P.M.	
Condition of ground	Firm	Loose	Firm	Loose
Ground Surface	11.6	9.6	31.0	36.4
5 cm depth	13.8	12.4	27.6	29.0
10 cm depth	15.4	16.4	24.2	23.8

In both places the early temperature increases with depth, while the afternoon temperature *decreases.* (*Out*going and *in*coming types of radiation.) But on the loosened ground, the diminished heat conductivity causes it to be colder by nights (hence more danger of frost!) in the upper 8 cm or so of soil, and hotter by day, than on the

untilled, denser soil. Below a depth of 8 cm within the ground, the conditions are reversed, for in the loosened soil the heat exchange is mostly confined to the layers near the surface, while in the denser soil the deeper penetration of the daily range of temperature leads to higher day temperatures and lower night temperatures in the deeper layers, than is true for the looser soil.

Next to tillage, it is the water content of the soil which particularly influences its temperature conditions and those of the adjacent air.

Rainwater and snowmelt carry along their own temperatures as they penetrate the ground and affect its temperature. F. Becker (287) published the temperature record which is reproduced as Fig. 69, and which was obtained from electric thermometers at Potsdam.

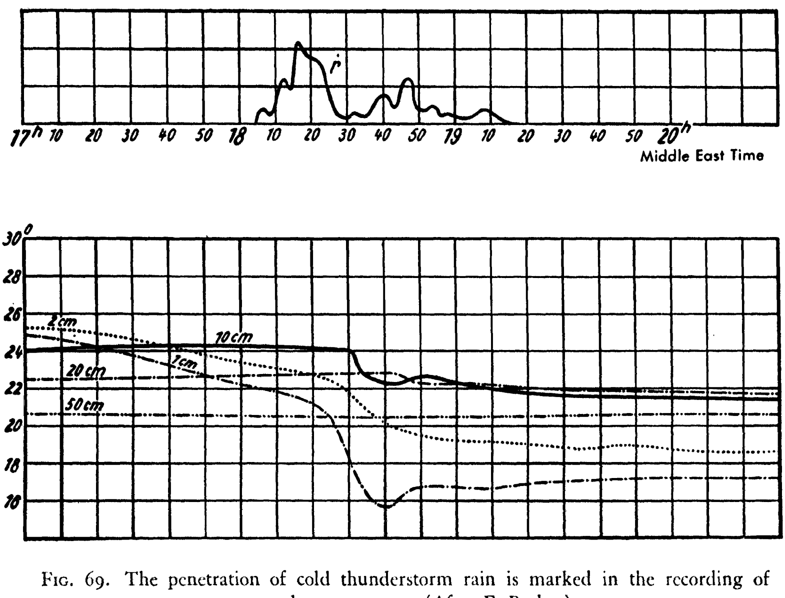

Fig. 69. The penetration of cold thunderstorm rain is marked in the recording of ground temperature. (After F. Becker)

The lower half shows the temperature march, the upper half that of the precipitation, on July 3, 1936, at which time a thunderstorm caused a 20.8 mm rainfall. Nineteen minutes after precipitation began, the thermometer at a depth of 1 cm shows the first effect of the cold rain water. This relatively long time includes the wetting resistance of the ground surface, for the water requires only 3 minutes

to penetrate from 1 cm to a depth of 2 cm, 6 minutes from 2 to 10 cm and 10 minutes from 10 to 20 cm. Such splendid automatic records of rain water penetration are very rare, and can be obtained only after such a heavy downfall as that in the preceding example. T. Bălănică (*286*) could find no similar instance among the ground temperature records made near Munich.

F. Albrecht (*374*) gives the month of July 1937 as an example of one in which there was a close correlation of precipitation and soil heat conductivity. Fig. 70 in its upper portion gives the rainfall

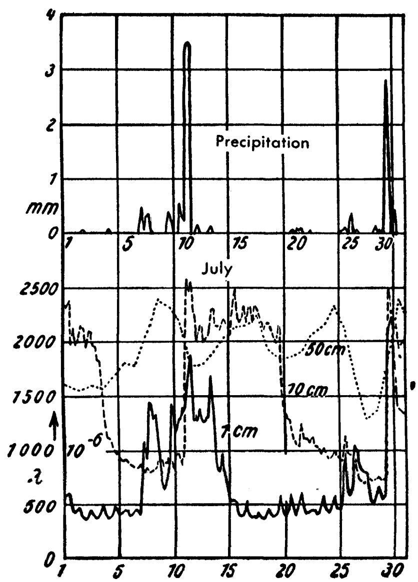

FIG. 70. Relationship between precipitation (at top) and heat conductivity of the ground (lower group of curves). (After F. Albrecht)

for each of the 31 days. Underneath is the record of the heat conductivity of the soil at depths of 1, 10 and 50 cm. They were obtained by means of the Albrecht heat-conductivity meter.

It is at once evident that high conductivity corresponds to a moist soil. In other words the poorly conducting air in the pores of the soil is replaced by better conducting water. In the layers near the surface the ground is generally — and especially in dry weather — drier and consequently of poorer conductivity than at a greater depth. The 1 cm curve follows the precipitation closely and without

lag. With depth there comes a phase displacement; at a depth of 50 cm (dotted curve) it amounts to several days. In dry weather the 1 cm curve has a decided daily cycle as Fig. 70 clearly indicates. Albrecht explains it as "the stronger pressure of the then highly heated sand," but perhaps a simpler explanation is the daily range of soil humidity, for which L. A. Ramdas and M. S. Katti (*301*) have furnished many recent data.

Since the water content of the soil undergoes constant fluctuation, the heat conductivity of the soil varies with time and weather. J. Schubert (*22*) proposed separating the heat capacity of the soil into two components to begin with — namely, the heat capacity of the dry soil, and the supplementary component resulting from the water content. The former is a soil constant which does not change for a given place. The latter takes into account temporary variations. It is equal to the water content of the soil if we relate heat capacity to unit volume rather than as is customary to unit mass.

Many previous attempts have been made to determine the influence of soil moisture on soil temperature. The earliest measurements known to me are those of E. Wollny (*305*). Fig. 71 shows

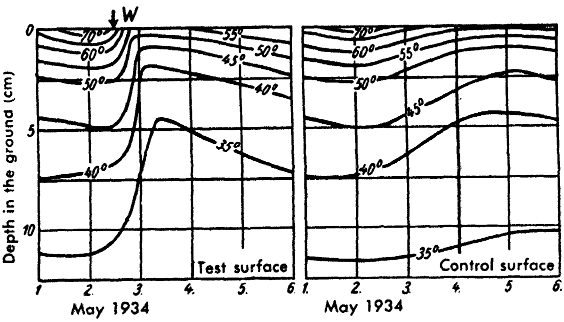

FIG. 71. The influence of artificial watering (*w*) on the ground temperature. (After tests by L. A. Ramdas and R. K. Dravid)

an experiment made by L. A. Ramdas and R. K. Dravid (*300*) in 1934. The left half of the chart shows the experimental surface; the right half, an untreated surface for comparison. The temperature curves are drawn from ground temperature measurements at about 2 P.M. from the first through the sixth of May, 1934. At 6 A.M. on the second day of the test (Point *W*), the ground was artificially watered. The resultant cooling causes the isotherms in the ground to rise suddenly. As can be seen from the control surface, the weather

caused a cooling on the following day. The effect of the watering, however, was outstanding from the beginning and was still evident on the sixth day.

O. Fuchs (*289*) studied the influence of soil moisture on the adjacent temperature field for a limited area. His purpose was to determine the connection between the rising wind fields which favor gliding and the condition of the soil in the neighborhood of Darmstadt. In this connection thermal convection appeared closely dependent on ground water. A fall of temperature appeared from dry to moist areas; in places of abrupt temperature contrasts in particular the removal of heated air from the ground set in.

The work of G. Krauss and collaborators (*296*) shows how soil humidity can vary within a limited area and so determine forest habitats.

The variations of the soil and their influence on the heat economy of the ground are made evident to an attentive observer through three meteorological processes. These are: the melting of freshly fallen snow, the formation of frost, and the formation of glaze.

Snow forms in the higher air layers, so that snowfall is independent of the microclimate: If we travel through mountainous country when the temperature is somewhat above 0°C, and wet snow is falling, we can observe over wide areas that the lower limit of snowfall coincides with an isohypse.

As soon, however, as the snow covers the ground and the action of radiation, wind, ground warmth, etc. set in, the microclimatic variations quickly become noticeable—and the more quickly, the thinner the snow cover. The lower limit of snowfall becomes ragged. On soils of good heat conductivity the boundary quickly rises to higher levels and under the influence of heat streaming up from below, just as on slopes where the influx of radiation brings heat to bear on the snow cover from above and removes it.

H. Mayer (*299*) has recorded in a photograph a very fine observation on this subject, which we have reproduced in Fig. 72. In April 1933 the members of the Frankfurt Meterological Institute had come to visit the Research Institute on the Jungfrau pass in the Lauterbrunner valley. H. Mayer writes: "A final snow cover of about 10 cm thickness and 0°C lay on the warm earth whose temperature was above zero. The air temperature was also 0°C. On account of the low clouds there was only a weak, diffuse sky radiation, so that the snow was being melted principally by heat coming from the ground. The first snow to be melted was that on the living rock, then that on the meadows and the overgrown talus slope. It was

already completely melted away everywhere when we noticed one final snow-covered area in the midst of the green slopes before the Staubach valley. The falls of the Staubach dashing over 300 m down the vertical walls of a former glacial trough had formed a small erosion valley at its foot, in the solidified, overgrown talus slope. The talus newly formed in this cut bore a final snow cover. The

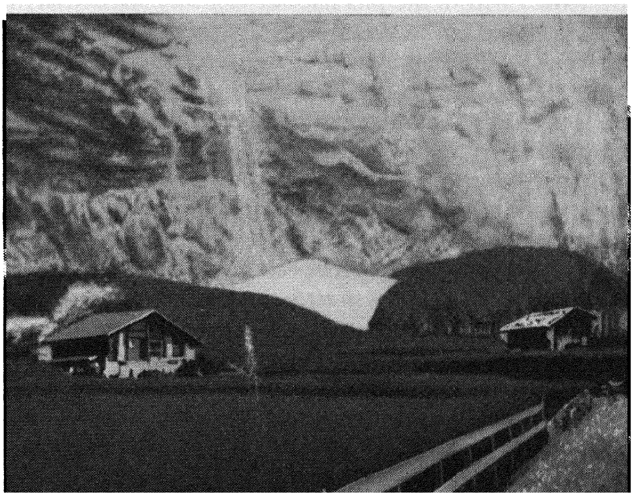

FIG. 72. The different thermal conductivities of the ground are evident by the melting snowcover. (Photograph by H. Mayer)

stone forming this cone, which has been brought down by the water in comparatively recent times, appears in its various features to have quite the same high heat conductivity as the ground. Nevertheless, the loose structure of this still unconsolidated talus determines its total heat conductivity through the air present in its interstices, and this conductivity is much less than that of the solid earth. The snow did not begin to melt until the weather cleared and the sun got to work."

Similarly conclusive observations can be made on the subject of hoarfrost. While snow falls everywhere and only its manner of melting discloses the microclimatic variations, the formation of frost is of limited occurrence. The time when frost melts should be observed. In the morning, board piles are still all white long after the well conducting earth has become dark.

A pipe connecting parts of a heating system betrays its location by a stain through the white covering of frost.

Several trees, with their root-balls of earth, were removed in autumn from a lane in the Munich court garden. Uniform care of the ground had soon covered up all traces of the filled holes. During the following spring, however, A. Schmauss observed that after cold nights the whole area of the former pits was white with hoarfrost. The still loose earth in the pits had lower heat conductivity than the surrounding older soil. Consequently, at night there was less heat transfer from the lower layers of the ground and the surface cooled off more.

Glaze is probably the most sensitive symptom of changing ground conditions. It is recognized that glaze forms in two ways, either through the solidification of super-cooled precipitation on the warm ground, or through the freezing of rain drops (above 0°) on the very cold ground. Whoever walks the streets with his eyes open when there is much glaze present cannot avoid astonishment, questions and research. Every street, every curb-side, every kind of ground, every kind of stone has its own glaze formation. Houses with central heating show an effect clear out to the sidewalk. Long-filled excavations at the side of the street are plainly visible. Surface roughness, the thickness and type of stone facings, the inclination of the ground — everything shows up. Truly, if anyone wants to take a hard test in microclimatology, let him take a walk when glaze has formed, and answer all the questions that Nature propounds!

We may add, incidentally, that such things as accidents resulting from glaze formation demand the attention of even the meteorological experts to these phenomena.

CHAPTER 15

The Air Layer Over Water

While on *land* insolation and sky radiation are caught by the ground surface, on *water* the radiation penetrates. To be sure, long-wave heat radiation is almost entirely absorbed by the first centimeter of water and even short waves are absorbed to a great extent. But visible light, as every swimmer knows, can penetrate to quite a depth. E. Sauberer (*325*) has made a classification of light relationships in inland waters. G. Dietrich (*310*) has recently published a complete description of such relationships in the ocean.

Ten to 40% of the total radiation from above penetrates to a depth of 1 m, depending on the purity of the water. Thus the absorbed insolation is distributed through a considerable vertical extent, in contrast to what takes place in the ground. But of still greater importance is the *movement* of the water. Under normal conditions there is always convection taking place in water, just as in air. It rapidly transmits to the lower layers the heat which is absorbed at the surface. Consequently the diurnal and annual temperature cycles make themselves felt more deeply in the water than in the earth. We shall first recall these facts from macroclimatology, which account for the difference between continental and maritime climates.

From the standpoint of microclimatology, however, it must be emphasized that besides the difference between land and water, there must be considered the difference between water and water. Conditions over the open sea are quite different from those over a lake, a narrow river, or a pool. While the interest of macroclimatology in water-surfaces is in proportion to their size, because then all opposing factors can be so much more easily weighed, microclimatology, here also, shows its love for the small. It is the very small water surfaces which give us the key to many questions of heat exchange in water and soil — questions which cannot be asked of the sea. The plant world, too, has closer relations with small waters than with great ones.

Just as it was necessary to touch the borders of geology in studying microclimatology on land, so here too, we verge on oceanography and limnology in orienting ourselves on the waters. But we shall

mention only what is indispensable to an understanding of the air adjacent to the water.

We have already spoken of the low albedo which characterizes a water surface. It is about 9% for the visible spectrum and 5% for the ultraviolet. Reflection is partially diffuse and partially direct. It depends on the altitude of the sun. The lower the sun, so much more effective is direct reflection from quiet water. Consequently the albedo, in general, is a function of solar altitude. Though, as K. Büttner and E. Sutter (*307*) have shown, for the ultraviolet alone the albedo is practically independent of solar altitude. Their explanation for this is that the greater part of the ultra-violet radiation falling on a horizontal surface comes not from the sun, but from the sky and hence is not from any particular direction. Perhaps the greater ease with which the short waves are scattered has some bearing on the question.

On the other hand a great increase of albedo with decreasing sun height is to be observed for the total radiation from ½ to 3 μ. Fig. 73, taken from the work of Büttner and Sutter, shows this dependence according to numerous measurements of the authors, made in the North Sea. Besides the data for naturally moved water, figures are also given on the same chart for wet and for dry sand, both of which have significance for coastal climate. As we already know, sand has a higher albedo than water, and dry sand higher than wet. From the zenith position of the sun down to an altitude of about 40°, the reflectivity does not change greatly, but from there on it climbs more and more steeply as the sun goes down. One hundred per cent for 0° altitude of the sun is the theoretical limit to which the measurements approach.

This fact has a practical meaning for the beaches, for inland lakes and the banks of the rivers. At steep vineyards the "underlighting" reflected from the river can yield considerable additional radiation. At the vineyards of the Steinberg near Würzburg, O. H. Volk (328*b*) observed by means of a Langè photo cell on a sunny day in February, i.e. at low altitude of the sun, an illumination by the sun of 16800, by the sky (light from above) of 8800 and by reflection from the river Main (light from below) of 16400 units (lux.). Five measurements brought about the averages of 6520 for light from above and 4280 from below. "The best situations for a vineyard (according to Volk) profit from this additional light. East and west of the Main valley, we find slopes in a few kilometers distance of the river which have equal exposure, inclination, geological substratum and

soil conditions which, therefore, have in no way characteristics different from the south — or west slopes of the Main-valley, and, despite this, have no vine culture at all or yield only very mediocre kinds of wine. Macroclimatic differences between Main- and Wern-valley do not exist. I was unable to explain the difference in vine

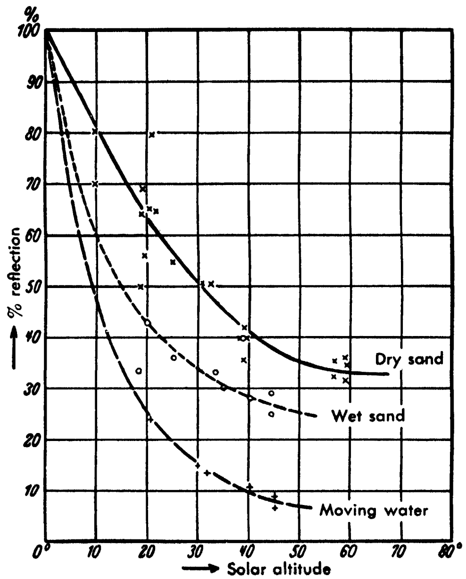

FIG. 73. Dependence of reflection number for total radiation on the altitude of the sun. (After K. Büttner and E. Sutter)

cultures until I became aware of the differences concerning the light from below and from above." Also with the wild growing plants this difference was significant.

As for the lakes, there the west shores receive a noteworthy additional reflected radiation by the morning sun and the east shores by the evening sun. In this connection, the preference for a westward sloping shore is, as H. Frey (*313*) mentions, mostly self-delusion; the western slopes are more often observed, because modern man is not an early riser by choice and seldom sees the eastern slopes in morning sunshine.

We shall now return to the temperatures in the surface layer of water, which forms the boundary of the adjacent air.

The recent data from the 1925–27 voyage of the German "Meteor," as worked out by E. Kuhlbrodt and J. Reger (*316*) showed a daily temperature fluctuation of the ocean surface amounting to only 0.26°C. Near the equator, where radiation is powerful, a maximum of 0.34°C was reached. There is therefore practically no difference between day and night in the upper layer of sea water.

It is somewhat otherwise in the larger lakes. On the part of meteorology, we have the studies of Lake Constance by E. Kleinschmidt (*315*), and W. Peppler (*320*) and the work of V. Conrad (*308*) and Wilh. Schmidt (*328*) on the Austrian Alpine lakes. The temperature range in these lakes does not depend entirely, as in the sea, on insolation and heat loss through outgoing radiation and evaporation. There is a heat exchange between the water and air, and between the water and the lake bottom. The air is partially controlled by the temperature conditions of the surrounding land with its more extreme diurnal and annual fluctuations. The effect of the lake bottom is greatest along the shore and in shallow parts of the lake and is extended up to the surface by means of convection within the water.

The diurnal temperature range of the surface water is chiefly governed by radiation. It is greatest at, or just before, the season when the sun stands highest; it is least in winter. According to measurements of F. M. Exner (*311*) in the Wolfgangsee, of W. Peppler (*321*) in Lake Constance and of V. Conrad (*308*) in four lakes of the Austrian Alps, the diurnal range in the surface water during the summer amounts to from 1 to 2°C; in winter it is only a tenth of that, or even less.

On a lake near Leipzig called the "Kirchenteich," which is 1.1 km long, about 200 m wide and has an average depth of 2 m, J. Herzog (*314*) carried out temperature measurements at seven depths from 1 to 250 cm. The place of measurement was 90 m from the shore. Fig. 74 shows the course of the temperature on a clear, almost calm summer day (July 17, 1934). The abscissa is the time of day; the ordinate, the depth of water. Along the upper edge are weather notes. The generally horizontal course of the isotherms in the lower part of the chart indicate the colder, deeper water, which is not affected by the daily range. In the surface layer the fluctuation is about 2°C, which is noticeably more than in the larger lakes.

W. Pichler (*322*) made a series of measurements near Leoben, Obersteiermark, in a shallow pool of about 12 sq m area and 40 cm maximum depth, lying at 650 m msl. At a depth of 1 cm (Aug. 1936) he found a daily temperature range of more than 10°C. It

decreased with depth to about 4°C at a depth of 40 cm. The pool was thickly filled with horse-tail rushes (Equisetum paludum) which greatly diminished convection in the water. For this reason, and not merely on account of the smaller lake basin, these pool measurements differ from those in the Kirchenteich and more resemble those on dry land. A. Merz (*318*) observed, in the algae-filled Pontelsee at Walkenried, even in cloudy weather, a daily fluctuation of 11.8° in the surface water.

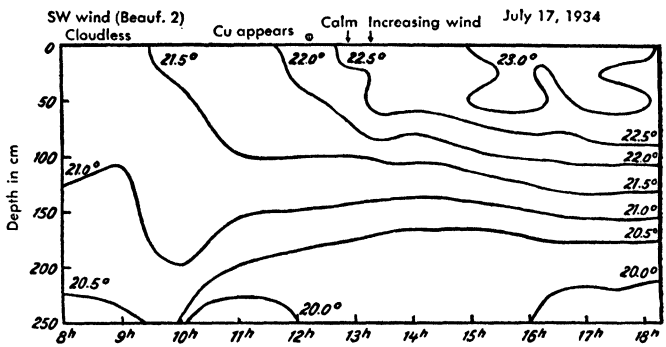

FIG. 74. Course of diurnal temperature in a small lake. (After observations by J. Herzog)

A glance at Fig. 75 will show how great is the similarity to temperature conditions in the ground. The temperature condition curves are for a fine summer day and a pool 40 cm deep. From the water surface down to a depth of about 30 cm, the lines run very similarly to those for the solid earth as shown in Fig. 15. The solid lines in Fig. 75 indicate warming from above in the course of the forenoon; toward midday they are bowed increasingly to the right. About 4 P.M. the first cooling at the water surface is indicated by the curvature of the tautochrone toward the left. The broken line curves which correspond to the afternoon and night, indicate the cooling off upward of the water layer near the surface.

There are two differences between Fig. 75 and Fig. 15. One is that the decrease of the daily range in water with increasing depth is much less than in the ground. We have only to compare the close crowding of lines at 30 cm depth in Fig. 15 with the spread at the same depth in Fig. 75. The cooler surface layer is evidently very shallow. Both are results of convection, which, in spite of the

braking action of water plants, is still active. It apparently increases the heat conductivity noticeably and at night permits immediate sinking of the colder, heavier water from the surface. Consequently from midnight to 7 A.M. there appears in the water a relatively thick isothermal layer below the surface, its thickness increasing until sunrise. The bend of the tautochrones to the left is confined to the first centimeter below the surface.

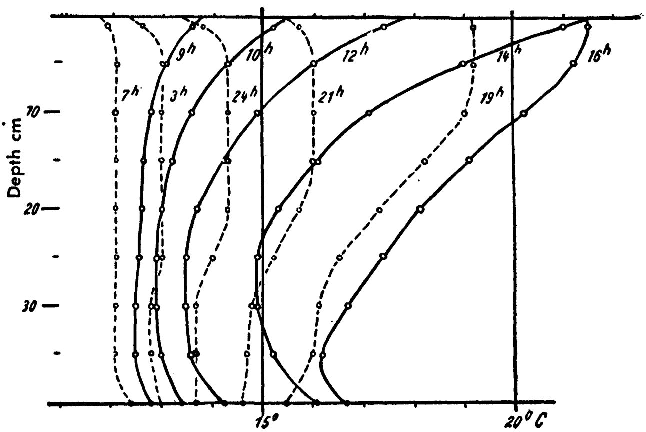

FIG. 75. Curves of the temperature condition on a clear summer day in a 40 cm. deep, pool of water in which horse tail rushes were growing. (After W. Pichler)

Fig. 75, on the other hand, shows an irregularity of the curve below a depth of 30 cm, which is quite absent in that for the ground. The lines are inclined above the bottom of the pool— mostly toward the right, but in the evening toward the left also. This indicates that the water is receiving heat from the bottom except in the evening, when the reverse is true. Since the maximum bending toward the right occurs about midday (2 P.M.) it is W. Pichler's opinion that the phenomenon results from a warming up of the bottom by direct radiation which penetrates the water. In the case of such shallow water, so filled with plant growth, we must also consider heat conduction by way of the more highly heated ground along the edges of the pool. This seems the more probable, since the maximum temperature at the bottom is not reached till 4 P.M.

With different depths of water, different subsoils and different plant growth, these measurements might have shown different results. They are well suited, however, to demonstrate the fact that

as water surfaces diminish in size the water temperatures are likely to approach those of dry land while still retaining their peculiar characteristics.

From a consideration of temperatures in the upper layers of the water let us now proceed to those of the adjacent air.

On the open sea the temperature difference between water and air depends on the origin of the air lying above the water. If it has come from a region lying poleward from the place of observation, the air is, in general, colder than the water. If it comes from nearer the equator, it is, in general, warmer. That is why, in the weather service, the temperature difference between water and air is used as an indication of air-mass origins.

The air adjacent to the water has to span the transition. In this equalization of advectively occasioned contrasts the significance of the air next to the water degenerates, for the influence of radiation processes upon it is hardly worth mentioning. It is not so long since we thought that, judging by the appreciable daily range of air temperature over the ocean, direct absorption of insolation by the air was important. But E. Kuhlbrodt and J. Reger (*316*) showed in the "Meteor" observations, that this apparent daily fluctuation of air temperature was due to the method of observing temperatures on board ship. Actually, it amounts to only 0.3 to 0.5°C which is scarcely more than that of the surface water.

On the open sea the air next to the water is of special character on account of the motion of the waves. The boundary surface between air and water is in motion; the lowest air is increasingly mingled with spray as the waves rise. When, in a heavy sea, the foam is beaten from their crests and thrown like mist over the surface of the water, when the horizon disappears and the air is filled with spume, then there is no more "air adjacent to the water" in a microclimatological sense. Water and air are at battle together. Consequently it is only under special weather conditions that it is possible to take measurements in the air layer next to the water.

In the Baltic, particularly the Bay of Mecklenburg, G. Wüst (*329*) has made temperature and humidity measurements with an Assmann aspiration psychrometer from the little, flat, ship's boat of a schooner. The result of the 26 series of observations for the first 2 m of air above the water is given in Fig. 76. The upper portion shows the temperatures; the lower portion, the vapor pressures—separately for the 17 series in which the water was warmer than the air, and for the 9 series in which the water was colder, the latter

chiefly in the midday hours. There are no evidences of definitely in- and out-going diurnal types of radiation in either diagram, dependent on the time of day.

Up to 20 cm the two temperature curves are practically opposites. From 20 to 50 cm the air temperature increases, slowly at first, then suddenly faster. At zero height in Fig. 76 is the tempera-

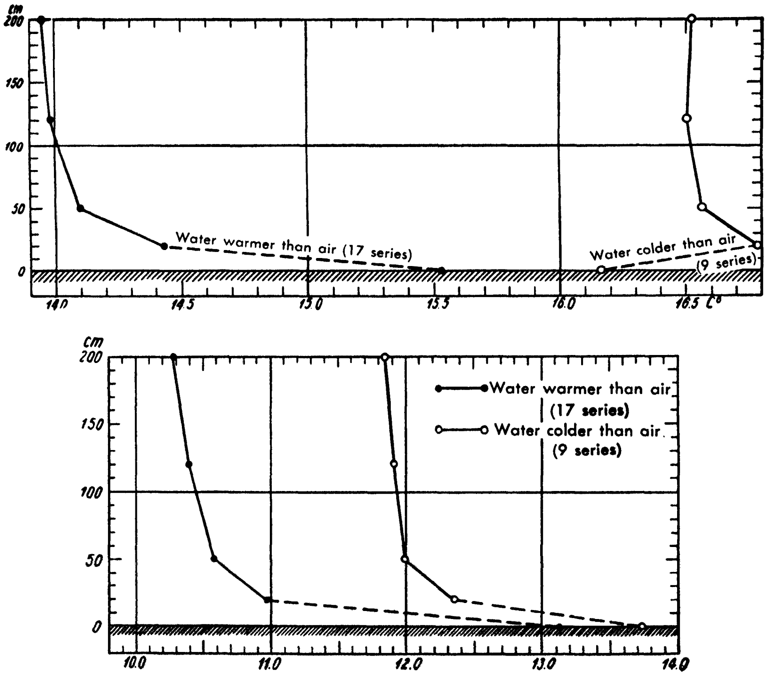

Fig. 76. Course of temperature and vapor pressure in the layer of air directly over the water — in the Baltic. (After G. Wüst)

ture of the ocean surface, which in most cases is warmer than the air at 20 cm, but in other cases is cooler. G. Wüst draws this conclusion: "Normally the temperature stratification close above the water of the open ocean represents a condition of unstable equilibrium." Perhaps later observations will show to what extent the summer season (the measurements were made between the 14th and 19th of Sept. 1919) and the nearness of land are responsible for this.

In the lower half of Fig. 76 the saturation vapor pressure corresponding to the temperature and salinity of the ocean surface is taken

for zero height. The course of both curves corresponds to the normal wet type, which we have already found for a solid surface which is giving off water vapor. (See Fig. 44.)

W. Findeisen (*312*) has demonstrated the probability, on the basis of observations of strip like wave formation on the thin water layer of the Neuwerk tidal flats, that the boundary layer of air lying on the water is partially laminar and partially turbulent. Water strips with a smooth surface correspond to laminar boundary layers; those with a wavy surface, to turbulent layers.

The investigations of W. Peppler (*321*) on the temperature of the air and the water on Lake Constance belong in the realm of macroclimatology, so we shall only mention them here. R. Marquardt (*317*) has studied heat and water convection over a water surface from ship and shore observations on Lake Constance.

In conclusion we shall give some temperature measurements of Wilh. Schmidt (*327*) which he made on the shores of the Lunz lakes, according to the observational procedure which he has given for ground temperatures (279). Those listed in Fig. 77 were all made on Nov. 13, 1926 — a perfectly calm, warm and sunny autumn day. The temperature is taken as abscissa, with the 10° line solid and single degrees indicated by short strokes. The depth below the surface is taken as ordinate. The position of the measuring points is given at the right-hand margin of the chart.

Letters *a* through *d* correspond to the successive times of day — *a* being at 11:12 A.M., a time of strong insolation, while *d* was at 4:27 P.M. The upper series (a_1 through d_1) refers to measurements in a shallow bay in which the water on this calm day was absolutely motionless. Under the influence of insolation (a_1) the temperature maximum does not occur at the water surface, but several millimeters beneath. Wilh. Schmidt explains this as the combined effect of heat radiation penetrating the water, and evaporation cooling the surface. Part of the radiation penetrates as far as the lake bottom, 20 cm down, and there induces a secondary temperature maximum. This has already appeared in Fig. 75, and has come up under different, but similar circumstances in the air, in Fig. 9 for instance.

With decreasing radiation ($b_1 - d_1$) the temperature contrasts in the water diminish. The surface cools more and more, while the air above (d_1) cools still more under the influence of the neighboring land. (Compare d_1 with d_2.)

In the lower row there are given the simultaneous observations at three locations not far apart. Position II (heavy line) was in a pool

which, a few weeks previously, had been dry. The mud was still soft and impassable. Line a_2 on both sides of the ground surface, shows a finely developed incoming type of radiation such as char-

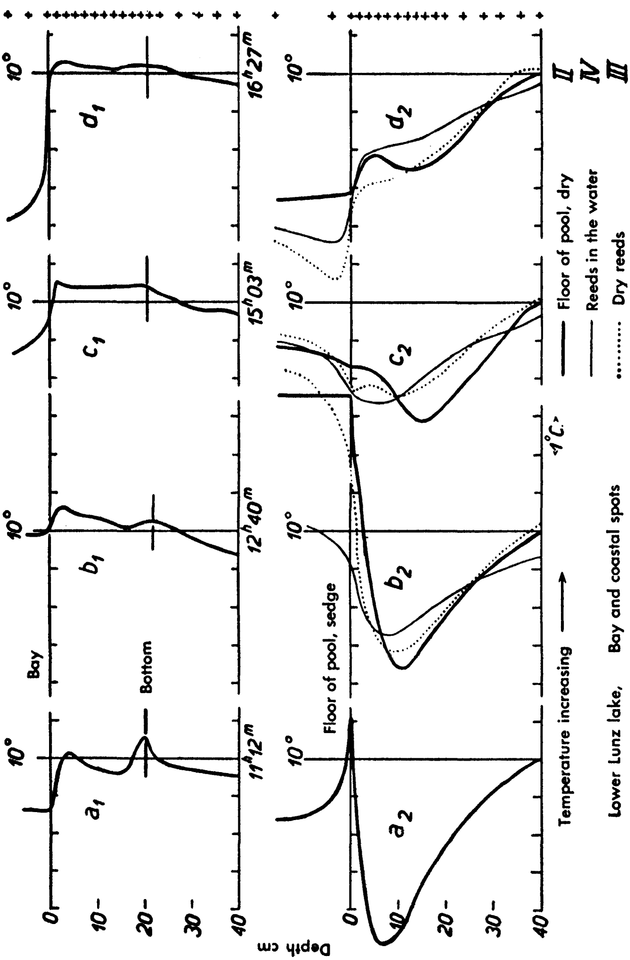

FIG. 77. Temperature course in the upper water layer and lower air layer under different conditions. (After Wilh. Schmidt)

acterizes solid ground. At a depth of 5 cm there is still a recognizable minimum, due perhaps to the effect of the wet ground (evaporation!) and of the preceding weather. A comparison of a_2 with a_1 shows how slight are temperature contrasts in water as com-

pared with dry land, and how completely different is the simultaneous temperature distribution in the first few centimeters of air above water from that at a similar height above land.

As the evening cooling process sets in, there occurs at Position II a temperature minimum at the radiating surface, which is at first a secondary (c_2) but soon becomes a chief, minimum (d_2).

The dotted lines in Fig. 77 belong to Position III which was located on a dry *shelf*, for the most part devoid of vegetation. The air near the ground at this point is somewhat cooler around noon (b_2) on account of the influence of plants near the ground surface (shading), yet at a higher level somewhat warmer (absorption of insolation) than above soil without vegetation (Position II). In the evening, however, (d_2) there is a decided cooling of the shelf and the cold air sinks between the grass blades till it is close to the surface.

The fine solid lines refer to Position IV which was near the lake shore on a shelf about 10 cm below the surface of the water. The temperature lines do not correspond to those in the open water (upper series in Fig. 77), but to those for dry land (II and III). The water held by the shelf loses its mobility; the shelf protects the water surface from radiation and becomes itself a medium of radiation exchange. It is all the same whether the foundation of the shelf is solid ground, mud or quiet water. Thus the temperatures in the uppermost water layer and in the lowest air layers merge, without noticeable discontinuity, into temperature conditions as we already know them to exist in and above the land.

CHAPTER 16

The Air Layer Near Snow

We have numerous measurements on the albedo of a snow surface, such as those of A. Ångström, C. Dorno, P. Götz, N. N. Kalitin, H. Lunelund, H. Olsson, F. Sauberer, and Ch. Thams. F. Sauberer (*350*) has published a recent compilation of results. The value for new snow ranges between 75 and 88%. P. Götz (*334*) obtained 100% several times during winter measurements in Arosa (1800 m msl). For old and wet snow the value goes down to about 43%. Plainly the figures for new snow are quite uniform within the spectral range from 0.35 through 2.5 μ. 80 to 85 was found in the ultraviolet, which is of the same order. But, as G. Falckenberg (*269*) showed, in the infrared around 10 μ, the snow is "black"—that is, it absorbs all the heat radiation which strikes it. According to Kirchhoff's law, this results in snow being an exceptionally good radiator for long-wave, nocturnal heat radiation.

The properties of the snow surface consequently have a like effect by both day and night on the heat balance of the snow cover. By day the insolation is to a large extent reflected, so that the snow can absorb little heat. By night, on the other hand, it radiates outward strongly, which lowers the temperature. This is where the high insulating power of the snow cover comes into play, as witnessed already by the table of heat conductivity of various types of ground cover. The nightly transfer of heat upward from the ground is thereby regulated and any storage of the day's heat worth mentioning is rendered impossible.

It is otherwise with the air above the snow.

Solar radiation which is reflected from the surface of snow returns into the atmosphere. Part comes back again to the snow surface, especially when a high degree of cloudiness favors reflection. The process is repeated, with the resulting high radiation readings which are obtained from measuring apparatus in the presence of a snow cover. Since they occur in the visible portion of the spectrum, we are accustomed to speak of a favorable "light climate" above the snow. A. Ångström (*331*) calculated that insolation with an original value of 1 increases to:—

1.02 through reflection from a snow-free ground under a clear sky,
1.08 under similar conditions, except a cloudy sky,
1.21 with a snow cover and clear sky,
2.10 with a snow cover and cloudy sky.

He took only 70% as the albedo for a snow cover. Actually observed radiation measurements substantiate these calculations. See further literature cited by F. Lindholm (*342*).

Air just above snow is therefore, subject to great contrasts. The heat balance of snow may be considered unfavorable. We found in Fig. 68, as we surveyed the different kinds of ground cover, that snow was in next to last place, it could absorb so little heat. The adjacent air is consequently influenced from underneath by very low temperatures. Nevertheless, incoming radiation is exceptionally great. Before we get into a discussion of this paradox we need to know even more about the snow cover — first of all as to its permeability by radiation.

Solar radiation and diffuse sky radiation can penetrate snow just as they do water. According to H. Olsson (*364*): — If J_0 represents the radiation penetrating the snow surface, and d_1 the depth of snow in centimeters, then the radiation J, which reaches the depth d, has the value, $J = J_0.e^{-kd}$.

This simple absorption law, mentioned by F. Sauberer (*350*) is strictly applicable only for an optically homogeneous substance, and hence is only approximately accurate in respect to snow. Furthermore, in practical measurements of nature, penetrating radiation, exclusive of the direct solar rays, there is always included the sky radiation, which has a complicated and continuously changing distribution over the face of the heavens. Nevertheless, the absorption coefficients k which have been derived, according to this law, from the observations are on the whole quite consistent.

Measurements with a photo-electric cell gave H. Olsson a value of $k = 0.074$, while a pyranometer gave $k = 0.114$. The cell is sensitive to a spectral range of from 0.3 to 0.7 μ, the pyranometer, from 0.3 to 4 μ. The difference is this: since the long waves are absorbed by the snow, an instrument which is sensitive to longer wave lengths will give a higher k value. Ch. Thams (*352*) found 0.083. F. Sauberer showed, for the range between 0.38 and 0.76 μ, that penetrability on the average was not closely related to the wave length of the penetrating radiation, and that individual values varied widely. For example he once found, under 7.5 cm of wet, fresh snow, more

blue and violet radiation than at another time beneath 3.5 cm of drier snow. His mean *k* value is higher (0.150). Pyranometer observations of N. N. Kalitin (*338*) gave doubtfully high *k*-values.

Summarizing all available measurements, we may assume that the value of the absorption coefficient *k* is somewhere between 0.07 and 0.12. Fig. 78 shows, for both of these extreme values, how much radiation gets through to a given snow depth *d*. These percentages do not refer to the amount of radiation striking the surface of the snow, for the greater part of this is lost by reflection from the surface.

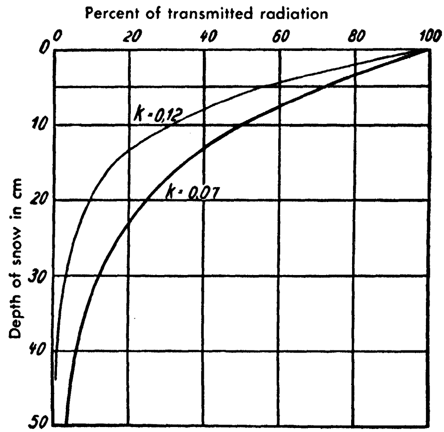

FIG. 78. Transmissivity of snow cover for radiation

face. The value 100 means, rather, the radiation which gets through the surface. Of this amount, as Fig. 78 shows, up to 50% reaches a depth of 10 cm, and (with $k = 0.07$) 10% reaches a depth of 30 cm. These are considerable amounts of radiation.

Solid objects such as twigs or stones lying in the snow may, under the influence of this penetrating radiation, attain a temperature above 0° and thus cause the overlying snow to melt from below. As the snow disappears on a sunny spring day it is common for stones and plants first to become visible in depressions and even cavities in the snow cover. We shall return to this later.

We still know far too little about snow's permeability to air. I can mention only the laboratory experiments in its determination, by O. Gabran (*333*), according to which it is equal to that of an equal thickness of splinter-free sawdust. Air permeability is of great

importance for the wintering of plants under the snow. The rotting of winter grain, for instance, is not a question of insufficient light but mostly a lack of air. If the snow glazes over or if several layers of ice form within it, its permeability to air is much impaired. No figures on this are at hand, however.

Alterations with and in the existing snow cover stand in close relationship to microclimatic processes. Whoever is interested in this subject should read the comprehensive and very interestingly written book of W. Paulcke (*347*).

Temperature measurements within the snow and on its surface are nowadays usually attempted only with electrical thermometers in order to avoid radiation errors and melting due to heating up of the instruments. In this way it is possible, by distant readings, to keep the field of measurement untrodden and untouched.

Recent measurements of snow temperatures we can credit to J. Keränen (*83*, *339*), E. Niederdorfer (*380*), and L. Herr (*80*) as well as O. Eckel and Ch. Thams (*332*). Fig. 79 gives an excerpt from the last mentioned work — the course of the isotherms in the snow at Davos during the winter of 1937–38. The measurements were made at 8 A.M. The upper boundary curve gives the depth of the snow as a function of time. The ordinate scale is in meters; at the middle of January, therefore, a snow depth of 65 cm was reached. In general the course of the isotherms is similar to that in the earth, as a comparison with Fig. 14 will show. Yet snow has some distinctive characteristics when considered as "ground."

In the first place its poor heat conductivity results in a crowding of the isotherms near the surface. (Fig. 79 gives them for unequal intervals — every 4° near the surface!) Deep within the snow, its temperature is only slightly below freezing, even when the air temperature may be as low as $-33°$. This illustrates how great protection is afforded seeds by a winter snow cover. Heat waves penetrate the snow considerably faster than do cold waves, for while the latter are transmitted only by true heat conduction, the former have the benefit of a pseudo-conduction through infiltrating water from melting.

Fig. 79 gives no indication of the daily march of temperatures within the snow. For this we must turn to Fig. 80 which is taken from the observations of E. Niederdorfer (*380*) at Eisenkappel (Kärnten) on Jan. 16, 1932. For a snow thickness of 20 cm he derived the arrangement of tautochrones there shown, based on measurements of the heat balance and temperature.

Radiant heat penetrates the snow deeply, for at a depth of 20 cm

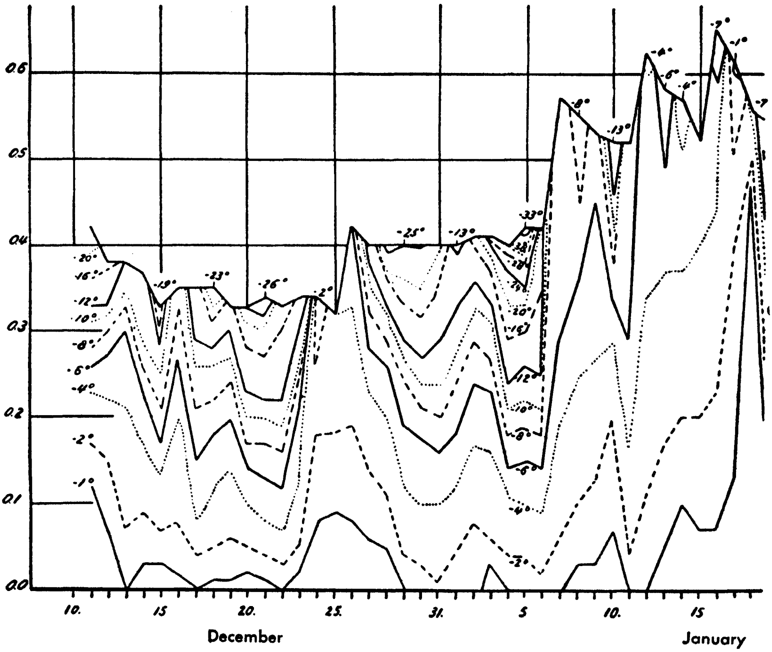

FIG. 79. Course of the isotherms in the winter snow cover in Davos. (After Eckel and Thams)

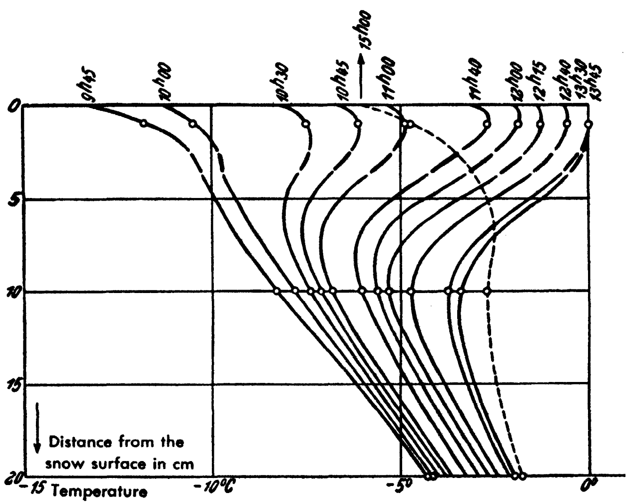

FIG. 80. Tautochrones of the snow cover temperature. (After E. Niederdorfer)

there occurs a temperature rise of 2.5° during the forenoon. The nocturnal type of radiation outward which is well represented by the 9^h45 curve, is replaced by the incoming type. The temperature maximum does not occur at the surface of the snow, however, but at a depth of 1 cm. The cooling effect of evaporation is present on the surface. We have the same set of circumstances which we have previously described as applying to air above the water. The type of temperature distribution designated in Fig. 77 as a_1, corresponds near the surface exactly to the midday tautochrones shown here in Fig. 80. In the case of the snow we have here the added effect, that the long-wave heat radiation of the snow takes place from only a very thin surface layer, while the short-wave incoming radiation penetrates into the snow. E. Niederdorfer suggests, on this point, that a snow distribution corresponding to this temperature stratification is often met with — namely 2 or 3 cm of powdery snow lying over wet snow.

From the temperatures of the snow itself we now return to temperatures in the air lying just above it.

In the first 25 mm above the upper surface of the snow, A. Nyberg (*345*) made careful and enlightening measurements at Upsala, employing electric resistance thermometers like those of F. Albrecht (*157*). Even in this thin layer the stratified structure of the air overlying the snow stands out clearly as can be seen in the charts which Nyberg has published. At night the outgoing type of radiation was well developed. Averaging numerous observations, he arrived at the following relation of temperature stratification to wind velocity:

TABLE 28

Wind Speed (m/sec)	Number of Observa-tions	Height in mm above the snow surface						At a height of 140 cm (extra-polated)
		1	5	10	15	20	25	
Full calm	37	−17.6	−17.0	−16.4	−16.1	−15.9	−15.7	−12.1
0.3–0.6	30	−11.5	−10.7	−10.1	− 9.8	− 9.4	− 9.2	− 6.7
0.9–1.2	21	− 9.3	− 8.7	− 8.4	− 8.2	− 8.1	− 8.0	− 6.4
1.8	20	− 4.1	− 3.7	− 3.5	− 3.4	− 3.3	− 3.3	− 2.7

These figures demonstrate beautifully both the decrease of the temperature gradient and the increase of temperature as the wind velocity picks up. The temperature variation with height could be represented very satisfactorily by an exponential function.

P. Michaelis (*343* and *344*) has, from a botanical standpoint, made

a thorough study of the air layer adjacent to snow in the mountains. R. Geiger has made measurements at Munich with thermometers as test bodies, of which we have already spoken and of which more will be said later. Fig. 81 shows three examples which illustrate the most important processes.

The upper record of Jan. 9, 1935 was made as snow was beginning to fall. At about 2 A.M. all temperature differences in the air just above the snow have disappeared under the influence of cloudy weather. The stem thermometer lying on the ground is covered with snow in the succeeding hours. In the air adjacent to the snow the temperature is slightly retrogressive for the snowfall produces cooling, the thermometers become moist and lose heat by evaporation. The protection of the snow cover immediately makes itself felt in the thermometer. The snow insulates it against the action taking place in the lower air layer; outgoing radiation ceases and ground heat from below becomes effective. Five hours after the beginning of snowfall, the thermometer on the ground is already 5°C warmer than the one in the air just above the snow. The old rule: "Snow saves the seeds" can be read directly from the record.

The second record in Fig. 81 is an example of conditions in freezing

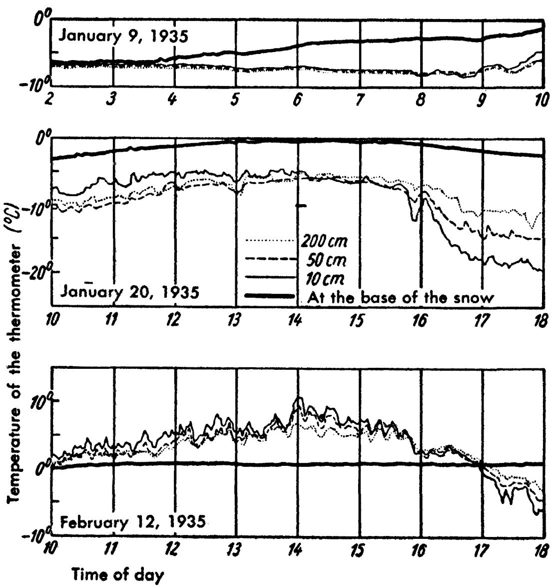

FIG. 81. Temperature recordings in the air layer over the snow at beginning of snowfall (above), during frost-weather (middle) and during thawing weather (below)

winter weather. On Jan. 20, 1935 the depth of snow cover amounted to 9 cm. In snow the temperature fluctuations are very slight; the diurnal march appears in the rise of the heavy line till 2 P.M., with subsequent decline. In the air near the snow, however, there is great temperature unrest, which is familiar to us from our acquaintance with the air layers just above the ground. The greatest fluctuations occur, not at the surface of the snow (for there air friction is too great) but directly above. A. Nyberg (*345*) found 1 cm; M. Franssila (*377*), 5 cm.

In the course of the forenoon, incoming radiation prevails, though irregularly and not very clearly. After the weather clears up, at about 4 P.M., outgoing radiation is quite evident. The thermometer at a height of 10 cm cools to $-20°$; that at 2 m, only to $-10°$.

The third record in Fig. 81 represents a thawing snow cover 6 cm deep, on Feb. 12, 1935. The temperature throughout the snow is 0°. The thermometer lying on the ground records a few tenths of a degree above zero at times, because it is absorbing the penetrating radiation. The daily course of the temperatures above the snow proceeds very irregularly. At noon the temperature of the stem thermometer a few centimeters above the snow rises to $+10°$C. In the meteorological shelter the air temperature reached only $+0.9°$C. If the ground beneath the snow is still frozen, vegetation is in great lack of water, for the movement of water from below is hindered by the grip of winter. In the air near the snow, however, the evaporation requirements of spring are ushered in by high plant temperatures.

Toward evening the temperatures again drop below freezing, and cut the line of the snow temperature at a sharp angle. Incoming radiation, which is particularly evident between 2 and 3 P.M., gives way to the outgoing type.

From observations at the observatory of the Air Weather Service in Munich during the winter of 1934–35, the average distribution ranges of air temperatures above the snow have been worked out by R. Geiger (*335*) as shown in Fig. 82. There are three different groups of observations: in the upper portion of the chart, days with freezing weather and an old snow cover (22 days); in the middle portion, days with air temperature prevailingly above 0° and an old snow cover (9 days); and below, days on which remnants of a snow cover still lay on the ground (7 days).

The shaded columns show, in relation to height above ground (ordinates) the temperature province within which the temperatures of the thermometer varied. The left-hand column refers to

the hours from 5 P.M. to 7 A.M.; the right-hand column to those between 9 A.M. and 2 P.M. The temperature scale is at the bottom; the frost line is especially marked by the vertical line in each of the three sections of the chart. The thickness of the snow cover is indicated by the dotted areas. The positions at which measurements were taken are shown by small circles.

The two small stars above each portion of the chart give the average true air temperature in the meteorological shelter for the same

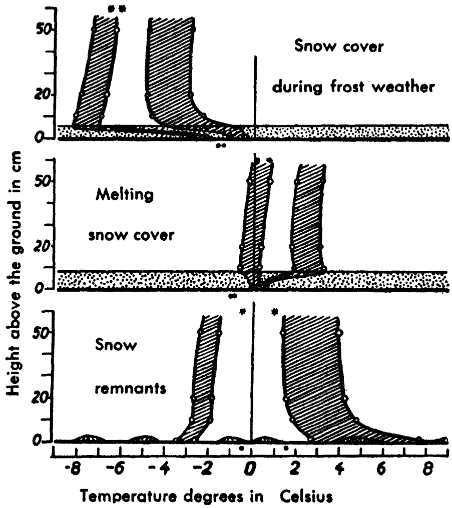

FIG. 82. Range of temperature distribution during the day (right) and night (left) in the air space near snow

periods of time in order to facilitate comparison with the macroclimate. The two points below the ground surface correspond to simultaneous ground temperatures at a depth of 1 cm.

For all three parts of the sketch, the common characteristics of the climate close to the snow are these: —

1. In contrast to temperatures within the shelter the temperature picture of the air near the snow is one of extremes, particularly so at the snow surface.

2. The temperature scattering (indicated by breadth of the shaded areas) is greater by day than by night, and as we leave the surface of the snow, it decreases upward slowly, but downward very rapidly.

3. In the air close to the snow, incoming radiation predominates by day and outgoing by night, just as over earth.

The lower part of Fig. 82 especially is practically the same as for bare ground. The diurnal surface maximum is very pronounced. Here, for the first time, positive temperatures appear at a depth of 1 cm within the ground. It is a situation favorable to *snow-smoking* according to F. Rossmann (*348*). If the amount of bare surface considerably exceeds the amount of snow surface remaining in isolated banks, if temperature and humidity are high, and if the wind is very light, a very fine fog may be seen at times over the snow banks. The veil of fog forms on the windward side of the snow surface and dissolves not far beyond the lee edge. On May 26, 1931, F. Rossmann succeeded in apprehending the conditions of this microclimatological process on the summit of the Feldberg in the Black Forest, using the Assmann aspiration psychrometer. To windward of the snow bank he observed, as the average of several series of measurements, 18.1°C and 82% humidity; in the lee, 15.2° and 89%. The phenomenon arises therefore from a cooling against the snow bank of the warm air current close to the ground.

Now let us return to Fig. 82 and consider conditions during freezing weather. Imagine the conditions facing a young plant that looks out over the snow. Its foot is in the province of winter rest and protected heat. The part which extends up to the top of the snow is exposed to the sharpest radiation frost. A few millimeters higher is full insolation and the strong reflected radiation of the snow surface on stem and branches. Then there is the wind to consider, to which is added drifting snow at times. All this is against plant parts which have not been accustomed throughout their growth to the demands of a microclimate close to the surface but, on the contrary, have been unexpectedly subjected to them by the accidental height of the snow. In Fig. 55 we saw evidence of the consequences.

Through the heating action of those parts of the plant which appear through the snow, the snow which lies against them is melted away. This induces the formation of a cavity melted out around every stem, twig and blade of grass, in which the plant stands as in a funnel. This funnel usually extends further on the sunny side than on the shady side.

This process is diagrammatically shown at the left in Fig. 83. At the right we have another frequently observed phenomenon of melting. Suppose there has been fresh snowfall during the night. (Sketch 1). The snow heaps up somewhat about a blade of grass. The next day let us suppose the temperature of the snow is such that, under the influence of insolation, it just begins to melt on the slope facing the sun. The following night the water which has formed

at the surface freezes into a thin sheet of ice (Sketch 2). On the next day this is penetrated by the insolation almost perfectly. As proof of this, F. Sauberer (350) found, behind a 25 mm sheet of ice, 84 to 87% of the radiation falling on its face. The little ice plates

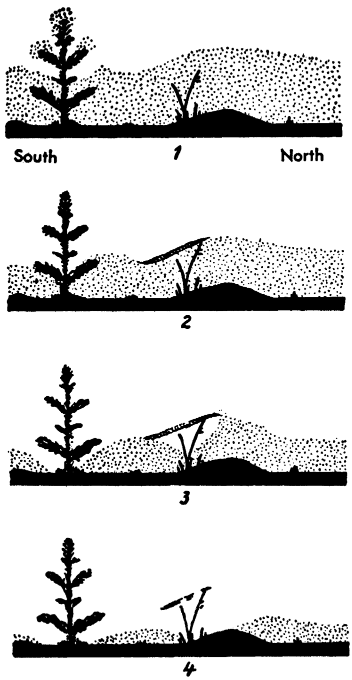

FIG. 83. Melt-craters and ice-sheet formation at the thawing surface of snow.

to which we refer are, however, only some 1 to 3 mm thick. They melt not at all or very slowly and remain a long time on the changing and settling snow cover. When they reach the points of grass or other plants the ice plate is left there while the transmitted insolation melts away the snow from the grass beneath. There often result great "glass-covered" cavities in which high temperatures must prevail (Sketch 3). Sometimes the ice plates remain for a while after the snow has all melted away (Sketch 4). On stubble fields whose uniform rows give rise to a series of ice plates on the south side, one can see rank after rank of such ice plates. On account of their permeability to radiation they last a long time in freezing weather, melt where they lie and crumble with time.

CHAPTER 17

The Air Layer Above a Sod Cover

How relationships in the air layer near the ground vary in the presence of a plant cover and how the interaction proceeds between the microclimate and the living plants will be the subject of the sixth section. Here we shall speak of plants only insofar as they alter the nature of the ground surface. In this case the plant cover causes no changes within the lower air, but this air layer as a whole is affected by the living ground-cover just as the air above sand possesses different properties from that over rock or over an asphalt street. Consequently we shall have much to say about this ground-cover in this fourth section, which treats of the influence of the substratum on the microclimate.

Observations in the air adjacent to the ground are frequently carried out over a clipped turf, for this kind of "ground" can not only be kept uniform and level without much care, but, best of all, it is not altered by rain and storm. Most civilized countries make use of observations with a "grass-minimum" thermometer at 5 cm above the ground, in order to verify microclimatological night temperatures in the macroclimatic network. The international commission for agricultural meteorology has recommended for observations in the lower air the following standard procedure (23): "There should be a uniform ground cover within a distance of at least 15 m about the installation. In climates where it is possible, the ground cover should be a uniform sod." The previously mentioned measurements of N. K. Johnson and A. C. Best were made under such conditions. Under these circumstances a living ground cover is of particular, practical significance in microclimatology.

Now, what changes does the ground surface undergo when it is overgrown with plants? Back in Chapter 13 we mentioned the change in albedo of the surface of the ground. Of much greater importance for the heat economy is the fact that even most plant growth greatly alters the *form* of the surface. Short blades of grass or the leaves of very small plants, even if only a few millimeters high, capture a portion of the insolation and shade a corresponding part of the soil surface. An absorption layer of several millimeters in thickness is thus created, in place of the infinitely thin absorption

surface which bare ground presents. This prevents the occurrence of such harmfully high maximum temperatures around midday.

E. Leick and G. Propp (*362*) investigated the reciprocal relations between ground temperatures and plant growth at the biological research station on the Hiddensee Island. They say: "From measurements in very different localities it appears that a ground cover of vegetation exerts a strong influence on the heat characteristics of the substratum. Even the most scanty plant growth can considerably modify the extremes of bare ground." On May 28, 1928 at 4 P.M., for example, the authors found at different points a few decimeters apart (but all lying on a steep coastal cliff exposed to the afternoon sun) the following ground temperatures at a depth of 2 cm:—

Under bare, loamy sand	25.0°C
At a place partially overgrown with moss and grass	23.6°C
Under a thick turf	12.3°C

The true air temperature was 13.1°C. It may be assumed that the temperature difference which at 2 cm depth amounted to 12.7°C within a very small area, was much greater still at the surface.

Young plants, such as pine seedlings or beans, growing in particularly hot places sometimes burn off where they come through the soil, and die. E. Münch (*363*, *364*) called this phenomenon the "foot-ring disease." Careful notice discloses that the deadly burn does not occur at the surface of the ground but several millimeters higher up. The plant conducts heat relatively well and the ascending sap is as cool as the deep ground from which it rises.

E. Rouschal (*356b*) measured the temperature of the transpiration current thermo-electrically in old trees of the "Forstgarten" (forestry experimental station) at Tharandt near Dresden. The cooling effect of this current could be authenticated up to 3 meter height above the ground. With the foliaceous trees the pores of which are ringlike and easily passed through by the sap current, the effect was three to five times greater than with the coniferous trees and those foliage trees with scattered pores. He found e.g. at the root-neck of a chestnut tree a difference of 15°C between the conducting sappy wood and the non-conducting sun heated wood; even at one meter height still more than 3°C.

The relationships here are the same as in the measurements which K. R. Ramanathan (*274*) determined at Agra, on railroad rails set vertically in the ground. The following table shows the observed results on two selected days:—

TABLE 29

TEMPERATURES ON A VERTICALLY PLACED RAILROAD RAIL AT AGRA

Height above the ground	Oct. 25, 1926 2:45 P.M. (clear weather)	Feb. 5, 1928 2:10 P.M. (after a rainy night)
305 cm		26.5
183 cm	38.8	27.0
122 cm	39.4	26.7
61 cm	40.0	27.9
Rail on the ground	39.3	26.2
Ground surface	47.1	25.7
In the shelter (Macroclimate)	31.1	20.5

The highest temperatures were measured, not at the surface of the ground but at the first measuring point above it. The great height of 61 cm is occasioned by the excellent heat conductivity of the iron — probably by the accidental choice of a measuring place. The displacement of the maximum is practically the same as in the case of living plants.

When the plants have once covered the ground in mutual contact — when, as the forester is accustomed to say, they have "closed in," the foot-ring disease is no longer possible. For in place of the heat-absorbing ground surface we now have the heat-absorbing layer of vegetation covering the ground.

Besides the heat economy, the water economy of both the soil and the air next to it are altered by the living ground cover. It is almost superfluous to say that air humidity over living plants is higher than above sterile ground, for every plant must breathe in order to live. The observations of D. Szymkiewicz (*213*), given in Chapter 10, demonstrated this by the steep humidity gradient found in the air near the ground. Further data appear in Chapter 28.

Here, where we are concerned with a sod cover as a surface property of the ground, we shall first point out that the water economy of a bare soil is radically different from that of one covered with short turf. We have proof of this through measurements of water economy under natural conditions, which were made at a lysimeter site in Eberswalde. J. Bartels and W. Friedrich (*357*) laid out this installation at the Meteorological Institute of the Forestry College. Boxes 1½ cubic meters in volume were sunk flush with the ground, resting on scales by means of which they could be counterbalanced up to a weight of 100 g — corresponding to a precipitation depth of 0.1 mm. Since the precipitation on the surface and the penetra-

tion of the water to the deeper soil layers were to be observed directly, conclusions could be drawn from the change of weight, as to actual evaporation or dew-fall.

J. Bartels (*355*) worked out the results of comparative measurements, over a three-year period, of bare sand as against a close-cut sod surface. Evaporation from a Wild cup — i.e. an open water surface — placed in the meteorological shelter, was used as a standard for comparison. For the months of May–August, 1930–32, he found the average evaporation in mm to be: —

TABLE 30

	From sand surface	From sod surface	From water surface
On days after rain	2.38	2.80	2.24
On clear days	0.47	2.15	3.61
On drought days	0.26	1.14	3.80

The drier the weather, the more the sandy soil reduced its output of water, while the open water surface gave up all the more water. The drier it was, the more difficult it was for the sod to get water from the subsoil. It resembled the sandy ground in that its evaporation decreased with increased dryness. But its evaporation was always more than that of the sandy ground — as much as four to five fold, in times of drought, "The oft-repeated observation," says J. Bartels, "that the bare ground in every respect suffers by comparison with that which is covered with vegetation, is completely refuted by our data, in respect to water content."

The average yearly evaporation from the sod surface was 189 mm more than from the sandy surface. This excess equaled 28% of the annual precipitation. These 28% were consequently extracted from the soil by the growth of the ground cover. This amount of 189 mm was actually greater than the total annual evaporation from the sand surface. During the growing season — April through September — the excess amounted to 39%.

The relationships of temperature to atmospheric humidity in the air layer near the ground — over sterile, as compared with living, ground — may be readily understood from the sampling tests of W. Knochenhauer (*361*) at the Hannover airport. One evening when the wind was still and a light dew was forming, he made some measurements with an aspiration psychrometer over both the run-

way at the airport and the adjacent sod, at four distances above the ground. His results are given in Fig. 84.

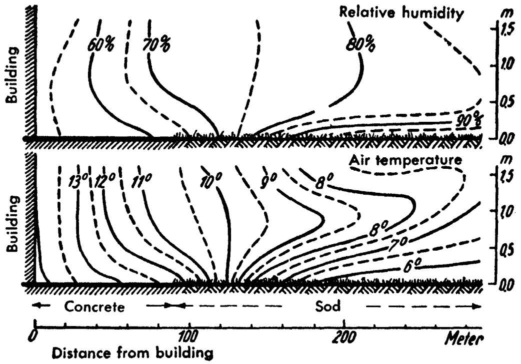

FIG. 84. Influence of runways and grass cover on the air layers near the ground on an airfield. (After W. Knochenhauer)

The upper half of the sketch shows the distribution of relative humidity; the lower half, that of the air temperature. The undermost air layer, 1.5 m in height, is in both cases shown in cross-section, from a building at the extreme left, across the field (which is about 90 m long) and on to a distance of some 300 meters. The observations were made between 10 and 11 P.M., when the microclimatic differences appear most clearly.

Looking at the sketch as a whole, the first thing to attract attention is that the lines of equal temperature and equal humidity run vertically rather than horizontally. The fact seems to be that it is warm and dry in the neighborhood of the building, but cool and moist out over the sod.

In the air closest to the ground, the iso-lines bend over to a horizontal position so that near the ground the contrast with conditions at a greater height is increased. Over the sod there is a cool, moist air layer; over the concrete, a warm, dry one. The influence of the latter is greater; for we have to go some 130 m from the building before the two conditions balance, with resultant vertical lines of equal temperature and moisture. About 1 m above the sod there is a region of maximum temperature; it is also noticeable on the humidity chart as a dry zone, though rather a weak one. It looks as though the warm, dry air which has formed over the concrete, moves slowly out at this height above the sod, overrunning the cold ground air.

H. Runge (*367*) has published a fine example from which we can recognize the effect of such microclimatic differences on local weather conditions. In an article written for the press in 1936, speaking of the danger of fog for motor cars and its alleviation, I found the remark: — "Careful observations have shown that even when there is heavy fog close to the ground, a layer of clear or only slightly cloudy air often forms up to a height of 35 cm or so. A high candle-power light reflector mounted very low at the front of a car with its light-beam directed obliquely downward and permitting no upward scattering may be of great help to visibility in driving on foggy nights." If this observation is true, it is no doubt based on the microclimatic distinction between the dry concrete road and the surrounding moist, cultivated land as shown in Fig. 84. Up to at least 35 cm the pavement controls the adjacent air layer.

As soon as the living ground cover is a few millimeters or, at most, centimeters high, an air skin close to the ground is formed. R. Geiger (*358–360*) has made some temperature records at Munich with cylindrical test-bodies which established quite well the temperature relationships in this thin air layer and the air directly above it. The test-bodies were cylindrical resistance thermometers in a nickeled sleeve 5 mm in diameter and 65 mm long (*167*).

Fig. 85 represents the distribution pattern of the temperatures for several hours on summer days in 1935 when there was no precipitation but plenty of sunshine. Only the lowest 40 cm of the ground air are considered. The ground temperatures (*B*) at points about 1 cm below the surface are on the chart displaced to a depth of 5 cm for greater legibility. The right and left hand boundaries of the shaded areas are the average absolute extremes within the given hours; in the case of ground temperatures the instantaneous values for the moments of beginning and end of the observation period are chosen as left and right end, respectively, of the heavy line. The slight spread of the ground temperatures makes them comparable on the chart.

Between 2 and 3 A.M. the nocturnal curve of outgoing radiation is recognizable only at a considerable height. Near the surface of the ground the temperature again decreases vertically upward and the already narrow spread is still further restricted. The effective zone of outgoing radiation at night is at the top of the grass. The air beneath this level is "anchored fast" as G. Hellmann says. In the morning (6 to 7 A.M.) it is first of all the surface of the grass which is struck and warmed by the slanting rays of the rising sun. There is incoming radiation above, but at the ground the outgoing

type still can be found. The temperature spread is very wide—corresponding to its rapid rise. As soon as the angle of incident radia-

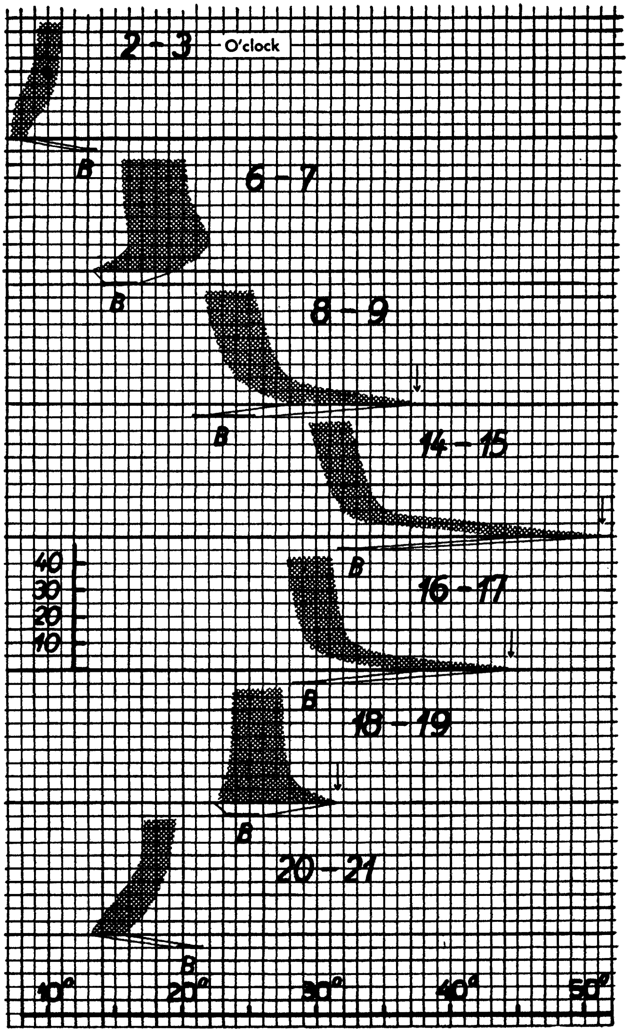

FIG. 85. Temperature stratification over sod in the course of the day

tion becomes steeper, the nocturnal situation in the living plant cover disappears, the conservative action of dew evaporation on ground

and grass is gone, and the air next to the ground begins to heat up as is shown by the curves of condition from 8 A.M. to 5 P.M. The small vertical arrow in Fig. 85 indicates the time of occurrence of the maximum temperature at the thermometer just above the ground. The ground and the air next to it follow this sudden heating only slowly.

The cooling of the grass-covered ground proceeds quite differently from its heating. For, while in the morning, the sluggish night air masses at the ground can be only gradually warmed up by means of heat radiated to them from above, the reverse process which involves their evening stabilization, takes place in all layers alike. The symmetrically proportioned figure for the hours between 6 P.M. and 7 P.M. shows this very nicely. The mean temperature is almost the same at all points. The right-hand boundary of the distribution area still reflects daytime conditions. With increasing cooling off the outgoing type of radiation sets in, appearing in its pure form between 8 and 9 P.M.

This brings us to a consideration of the influence of plant cover on the climate near the ground. Since this is reserved for Section VI, we shall break off at this point for the present.

SUPPLEMENT

On the Quantitative Determination of the Heat Economy of the Ground Surface

All the processes in the air adjacent to the ground are to our belief intelligible only if the heat economy of the ground surface is not only understood but also quantitatively apprehended. How the surface heat is introduced or dissipated has been described in the course of the 17 preceding chapters. The relative significance of the various factors has been pointed out. But the picture is not complete until the share of each factor in the total heat exchange is numerically known at every moment.

This desire of microclimatological research carries, however, far beyond its immediate tasks. It is a fundamental problem of general meteorology to investigate this exchange of heat at the surface since the condition of the whole atmosphere is determined by it. The problems of the quantitative description of the problem are here only outlined as a supplement. Further, one must point to the publications related to this subject.

In the nineties of the past century, Th. Homén (*378*) of Finland,

tried to determine the heat exchange with three different kinds of soil by observations. His results are now obsolete; with respect to the present state of science he underestimated the significance of the radiation process. F. Albrecht, Potsdam, (369–374) did pioneer work in this field; he inaugurated the first comprehensive observations (some results of which will be mentioned later on); his technical talents brought about a great number of instruments which serve exclusively to measure directly certain elements of radiation and heat economy; most recently, he succeeded in determining the heat economy, as far as its main elements are concerned, for all geographical latitudes for the solid ground as well as for the ocean. Besides, a Finnish scientist, M. Franssila (377) has carried on the heritage of Homén in a greater series of experiments at Pälkäne.

The heat economy of the ground surface is made up of four parts. The exchange of radiation should be mentioned first. Chapter 1 dealt with short-wave insolation from sun and sky; Chapter 2 and 5, long-wave outgoing radiation, radiative pseudo-conduction and wave length transformation. Accordingly as in- or out-going radiation predominates, the radiation exchange is positive or negative. F. Albrecht (372) constructed a radiation-exchange meter which permitted direct observation of the balance. S. Sauberer (382–385) in particular, in a series of works has studied radiation exchange as one factor in heat transfer.

Second is the heat gain (or loss, as the case may be) of the ground surface, which results from the influx of heat from deeper layers of the earth or its return in that direction. The third chapter was devoted to this.

As a third factor we may mention heat exchange with the adjacent air. It occurs chiefly through convection but also by advective processes — the moving in of warmer or colder air. Chapters 4, 6 and 7 dealt with these questions.

Finally there is the heat loss resulting from evaporation of water from the surface of the ground. In order to change 1 gram of water from the liquid to the gaseous state it requires an amount of heat which depends on the temperature of the water.

for a water temperature of	0	25	40°C
the vaporizing heat in calories is	595	582	575

This heat is withdrawn from the ground surface. In dew and frost formation this same amount is returned to the ground as heat of condensation. Consequently the heat exchange through the con-

densation or evaporation of water may be positive or negative. It cannot be overlooked.

Normally the heat economy of the ground surface is not in equilibrium. The interplay of the various factors greatly increases or diminishes the heat supply of the surface at a given moment. Its temperature is always rising or falling. Only on long winter nights in quiet weather can equilibrium finally be attained. It will be readily understood that it is much easier to compute the exchange with actual figures in such a case, than add it when in flux.

If there is a snow cover the task becomes still easier for then the surface is of uniform nature and form, while the transport of heat from the ground is small. Consequently a new series of heat exchange measurements has been carried out at night, directly over the snow. A. Ångström (*330*) in 1919 published measurements at Åbisco during the polar night when exceptionally stable conditions rule. In 1932–33 there followed the observations of G. Falckenberg (*376*) and F. Krügler (*148*, *379*) at Rostock and of E. Niederdorfer (*380*) at Kärnten. According to these the results of the nocturnal heat exchange of the snow cover in calories per sq cm per min. are as follows:—

TABLE 31

Author and Time Mean of "n" Separate measurements	Heat Loss	Heat Gain of the Ground Surface		
	Effective Outgoing Radiation	Through conduction from snow cover	Through convection	Through heat of condensation
E. Niederdorfer January, 1932				
Scattering	0.013–0.060	0.004–0.037	0.009–0.035	disregarded
Mean (n = 7) ...	0.052	0.024	0.028	
K. Krügler Winter, 1932–33				
Scattering	0.115–0.163	0.050–0.094	0.039–0.076	0.000–0.003
Mean (n = 8) ...	0.135	0.075	0.059	0.001

The four numbers correspond to the four factors of the heat exchange mentioned above. Among these, the influence of hoar-frost formation on the snow cover is very slight and consequently was at first neglected by E. Niederdorfer. Radiation is the main factor and a negative one. In a condition of equilibrium such as prevails on a winter night the heat lost by radiation from the snow surface comes

in about equal parts from heat conduction through the snow from the ground and from convection on the part of the adjacent air layer.

Further recent data on the heat economy of the snow cover may be found in the work of O. Eckel and Ch. Thams (*332*) and A. Nyberg (*345*).

The best and most recent information on the heat exchange over the course of a full day is to be found in the measurements of F. Albrecht (*370*) and M. Franssila (*377*). Fig. 86 gives their results. The four circles at the left are based on F. Albrecht's measurements at Potsdam on a clear day in each season, i.e. Apr. 5, 1925, July 19, 1925, Sept. 30, 1924 and Dec. 16, 1924. The upper right-hand circle, which represents Pälkäne in the middle of Finland (Lat. 61° N), is an average of seven daily series made by M. Franssila in June and August, 1934 and is placed for comparison with the summer measurements at Potsdam.

The upper semicircle in each case shows by the area of its several sectors the amounts of heat brought to each square centimeter of ground surface in the course of the day — namely through heat transmitted upward from lower ground strata (line-shaded), through radiation from sun and sky (white), through contact with the adjacent air (cross-hatched), and finally through dew and frost formation (black). The lower semicircle shows in a similar manner the heat loss of the ground surface through the soil (conduction), through radiation to the overlying air (convection and conduction) and through evaporation. The unit of area is given at the lower right of the illustration.

In the heat economy of a normal day the intake and output balance. Therefore the upper and lower semicircles are equal in size. But according to season the amount of total exchange varies as is natural in view of the determining influence of the sun — in winter, small; in summer, great. The areas of the semicircles in Fig. 86 correspond to ±307 calories per sq cm per day in spring, in summer ±374 at Potsdam and ±394 at Pälkäne, in fall ±235 and winter only ±155.

In winter strong outward radiation rules the heat economy; incoming radiation is vanishingly small. The heat loss through radiation must therefore be made up by a return from the ground and by accession from the adjacent air layer. The illustration represents a winter day without snow. In the presence of a snow cover the part played by the adjacent air would be relatively more important. At no other time of year is it so closely concerned in the heat exchange of

the ground surface. This explains the especially strong winter recession of temperature near the ground with a snow cover.

If winter is the season when heat gain through frost formation can be counted on, it is in summer that the effect of evaporation comes to the fore — in Pälkäne more evidently than in Potsdam. The reason for this may be that in Pälkäne the June preceding the experiments

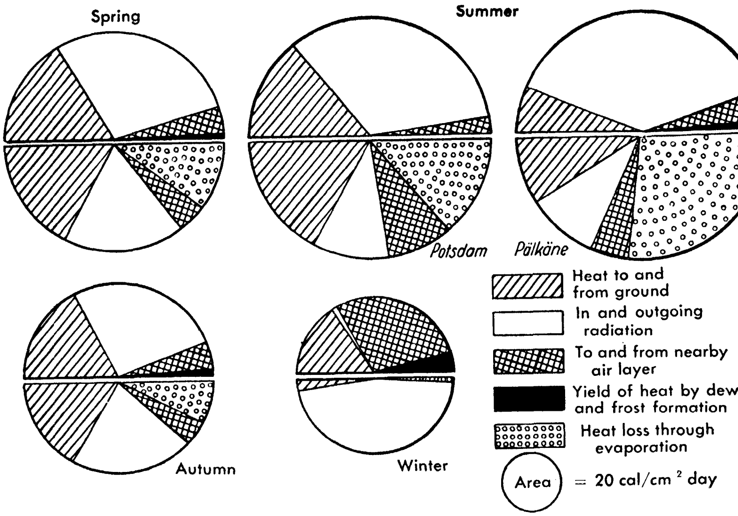

FIG. 86. Daily heat exchange of the ground surface in the different seasons

was a very wet month so that the ground was quite saturated. In Potsdam, consequently more heat could be carried to lower earth strata and into the air, while in Pälkäne it was used for evaporation.

In summer the most important factor is insolation. Indeed this determines the amount of the heat exchange. A considerable portion of it is again lost through nocturnal radiation outward on account of the high ground temperature, in spite of the short nights. The heat exchange in the ground alone remains essentially in equilibrium as in the transitional seasons. The heat surplus is chiefly used up in evaporation.

Finally we cast still a glance at the annual heat exchange in the different geographical latitudes. The following table contains the results of the investigation of F. Albrecht (*374a*). The third column of the table shows the entire annual heat exchange, i.e. the total of heat in cal/sq cm which passes through the surface of the ground in both directions.

TABLE 32

ANNUAL HEAT EXCHANGE OF THE GROUND-SURFACE FOR DIFFERENT GEOGRAPHICAL LATITUDES (cal/cm^2, year)

(After F. Albrecht)

			Gain of Heat of Ground Surface			Heat Loss of Ground Surface			
Geogr. Lat.	Station	Total Annual Balance	By Radiation	At the Expense of the Ground	At the Expense of the Air	By Radiation	By Transfer to the Ground	By Transfer to the Air	By Evaporation
1	2	3	4	5	6	7	8	9	10
71°	Station "Eismitte" of A. Wegener's Greenland Expedition	15,444	....	..	7,722	7,547	....	....	175
67°	Sodankylä (Finland)	23,214	11,607	...	...	...	1,689	556	9,362
52°	Potsdam	40,412	19,819	...	387	...	181	...	20,025
52°	Irkutsk	39,856	19,928	...	..	...	560	7,807	11,561
42°	Station of W. Haude's Expedition in the Gobi Desert	85,310	42,406	249	...	...	...	29,002	13,653
−6°	Batavia, Java	108,340	54,170	...	..	...	3,893	6,627	43,650

Since, above all, the sun determines the heat economy, the numbers are the highest at the equator and decrease polewards. The same is valid for the radiation economy (Column 4 and 7) if considered separately. While the balance is positive from the equator up to and beyond Finland, in "Eismitte" (station of the Wegener Expedition in the middle of the Greenland ice-cap) the outgoing radiation prevails by far in the total of the year. There conditions are valid for the year round as for our region in winter time, according to Fig. 86.

Immense heat amounts are used up for evaporation (see last column). Because of the increase of precipitation with decreasing geographical latitudes also these values increase generally towards the equator. But the climate at large scale is also influencing these conditions. In East Siberia, poor in precipitation, the heat amount used for evaporation per year is despite equal latitude and equal annual heat exchange essentially smaller than that at Potsdam which belongs to the humid climate of Central Europe. In the Gobi Desert, it is still much smaller than in Potsdam, despite the differences in latitude of 10°. It is very noteworthy that in the total of the year in the climate of Potsdam all heat spent by the sun is used up for vaporization of water. The amounts which the ground and the air layer near the ground absorb during the summer and which both give back during winter compensate each other finally.

But this is not true for all climates of the earth. Moreover, there are two regions where the air layer near the ground is obviously effective also for the total of the year, i.e. the frost climate and the dry climate. In the frost climate (Eismitte) the air layer near the ground must compensate the heat loss by outgoing radiation of the ground and the snow cover respectively. This amount of heat which must be compensated can be supplied only by advection of warm air from lower latitudes.

Conversely, in steppes and deserts, where the incoming radiation heat is only partly used up for vaporization, the air layer near the ground receives enormous amounts of heat. According to W. Haude, these heat amounts at his experimental station in the eastern Gobi exceed by 50% the entire heat exchange at Potsdam. There is a source region for the heating of the atmosphere and, therefore, it is worth while to study here the conditions of the air layers near the ground.

If we take into consideration column 9 of the table, we find, even in Batavia, a rather great transfer of heat from the ground to the air. It is to say that there the consumption of heat for evaporation is

enormous. Also about 4000 cal/sq cm which are mentioned in Column 8 as being supplied to the ground are used for heating the cold rain water originating from greater heights so that the surface layer does not essentially profit in heat. But as the tropics are abundant in heat something remains for the air layers near the ground.

In the paper mentioned before, F. Albrecht has determined the heat economy also for the individual months. There are also data given for some sea-stations. In this respect one must be referred to the original paper.

PART TWO

The Microclimate in its Relations to Topography, to Plants, Animals and Man.

Whoever reads the title of the second part of this book may at first have the impression that very dissimilar things have been included in this part. Land, vegetation, animals and man are united in their relation to the microclimate almost as in the case of a filing cabinet labeled "Miscellaneous."

However, as we enter the second part, we turn to a fundamentally different kind of microclimatic phenomenon, which will occupy our attention from now to the end of the book. In the first part we discussed the microclimates which exist near the ground as a consequence of their locations. We limited our considerations to the thin air layer, not over 2 m deep, which in the introductory chapter had been designated from the standpoint of the macroclimate as a "zone of disturbance."

Now we come to a second group of microclimates which are to be differentiated from macroclimatology not simply as a disturbing feature to be disregarded, but which were earlier considered by it and observed. The portion of the atmosphere in which these new microclimatic phenomena occur may exceed the limitation of a 2 m layer. This we shall show by some examples.

In Section V the influence of topography on the nature of the microclimate will be described. From this we choose our first example. In an alluvial valley, the climates on the flood plain, along the edge of the stream, on the slopes, and on the heights above, are quite different. It is indeed a climate of a very small space, since it varies with every meter that we ascend the slopes, and with every meander of the stream's course. But macroclimatological shelters can be put everywhere and variations determined according to accepted climatological methods. This has not been possible for any of the microclimates described in Part I.

Section VI will treat of the influence of the plant world. Imagine a little pine forest surrounded by meadows. For the macroclimate it is all one whether this little forest is there or not. But within the

forest there prevails a microclimate completely different from that of the surrounding meadows. The space from forest floor to roof is occupied by this climate within the timber-stand and we can again determine its properties according to the usual climatological methods.

Section VII is devoted to the relations of animals and man to the microclimate. When an architect builds a convention hall he creates within it, by the nature of the building, a special microclimate. The volume of air having the characteristics of such a microclimate may be enormous.

We come therefore to microclimates of a new order of magnitude. One might well ask whether the designation "microclimate" is justified on the whole, for this new kind of phenomena. It might seem desirable to insert between macroclimate and microclimate an intermediate classification which, according to the proposal of H. Scaëtta (*17*) would be best called a "mesoclimate." We should than be tempted to entitle the first part of this book "Microclimatology," the second, "Mesoclimatology." This would immediately indicate the unifying characteristic of the second part and wherein it differs from the first.

Yet it is only at first glance that this difference is justified. The nature of the country, the plant cover, etc., produce not merely mesoclimates only, but microclimates in the old sense. A furrow in the field has a special slope climate on either side; an anthill has one on all sides — both of which are, as far as they go, decided microclimates, which cannot be apprehended through the macroclimatic observation method. A single currant bush modifies the climate of its immediate vicinity even to the smallest volume relation. Yes, every leaf is surrounded by a film of air with its own special peculiarities. In this second part of the book, therefore, we deal with mesoclimates as well as with microclimates. Since, beside this, as was stated in the introductory chapter, the introduction of a new designation meets with difficulties of a general nature, it is best to retain the expression "microclimate" and employ it in the broadest sense. This is what we shall do in the second part.

In these days we hear and read a great deal about a "bioclimate." According to F. Linke, as he expresses it in 1934 in the foreword to his newly established "Bioclimatische Beiblätter of the Meteorologische Zeitschrift" it is "the science of the influence of natural forces on organic life." Bioclimatology is intended as a link between the so-called "exact" and the biological natural sciences, as is medicine. Since the microclimate is of decisive importance in the life of plant

and animal, bioclimatology and microclimatology, as Wilh. Schmidt (*20*) among others has carefully explained, find themselves in closest fellowship. In Sections VI and VII of this part, these bioclimatic questions will come more into the field of view of our consideration.

SECTION V

THE INFLUENCE OF TOPOGRAPHY

In investigating to realize the influence exerted by changing topography in the nature of the microclimate it is necessary to make a distinction as to the time of day. During the day, slopes facing in different directions and at different angles receive very different amounts of heat radiation. This is the most important factor in differentiating climates according to location. At night, on the other hand, it is the cold air which moves downhill and, independently of slope orientation, produces a variation of climate according to zones of elevation.

The following description takes into account this distinction as to time of day. Nocturnal relationships, being easier to understand, are treated first — in Chapters 18 through 20. Then in Chapters 21 and 22 comes a discussion of the microclimate resulting from action of various exposures to the sun. Only in the last chapters of Section V are the general questions of topographic influence taken up.

CHAPTER 18

Cold Air Floods and Cold Air Dams

Air of lower temperature is heavier than air of higher temperature. Cold air consequently endeavors to push itself under warm air. The result, if opportunity permits, is a circulation of different air bodies until equilibrium is attained. This is what happens at night in hilly country. Outgoing radiation first causes the formation of a cold layer of air next to the ground. Since this, equal ground conditions being assumed, at first is of equal vertical extent at all points, the cold air over the higher portions of ground is at the level of the higher warm air over the lower ground. This difference of density

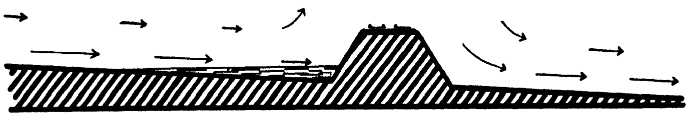

Fig. 87. Air drainage at night on both sides of a railway embankment crossing a sloping surface

in a horizontal plane results in a balancing movement. The cold air from the high ground flows to the lower places and is replaced by warmer air from above these lower places. The potential energy thus expended is so small however, in consequence of the small dimensions and temperature differences involved, that it takes a long while for the exchange to take place and it cannot continue if there are other meteorological factors to disturb it. The process works best on calm nights when the air pressure is high and the sky clear. Under such circumstances there are formed the widespread, often observed phenomena, known as "cold islands," "frost holes," "cold lakes," "cold air puddles" or whatever other name may be given the local formation of areas of low temperature at night.

The expression "cold lake," implies that cold air behaves like water, which always flows to the lowest point. We speak of a "flood of cold air." This comparison, as we shall see in Chapter 19, is only partially correct. It teaches us two things, however: 1. That concave land forms are always cold islands at night, 2. That objects which

impede the flow of air may be of great importance to the distribution of nocturnal temperatures.

An example may show just how far the analogy holds good between the circulation of cold air and flowing water.

Where a railroad embankment crosses a gently inclined plain at right angles to the slope the adjacent area above it where the air is dammed up is usually colder and more liable to frost than that on the down-slope side where the air cooled by radiation is free to flow on down and make room for warmer air from above (Fig. 87). Gardeners on opposite sides of the embankment must raise different kinds of flowers, for what luxuriates in the favored location, freezes in a nearby area.

This "cold air flood" is noticeable in the distribution of nocturnal minima within very limited bounds. As our first example we shall mention observations which R. Geiger (796) made in 1925 on a "frost area" in the neighborhood of Munich. These frost areas are young pine plantations of large extent. They originated at the time when the "Nun" ruled the forests around Munich between 1889 and 1891 and reforestation was slow in recovery. In many pine nurseries the young shoots of the plants froze year after year, even in June, so that many died, although part of them survived with great difficulty. Such plantings, almost destroyed by frost, are known as frost areas or frost fields.

The frost flats which were the subject of investigation were located in the Anzing-Ebersberg forest, some 22 km eastward from Munich. Fig. 88 is a sketch of the experimental field. On the right side is shown the contour map according to the data from a special survey. To the eye the surface appears flat but, as the contours show, there is a slight slope toward the northwest (notice the north arrow in Fig. 88). The air which at night flows approximately at right angles to the contours is dammed by the high growth of pines which surround the frost flats on the north and west, as shown in the left-hand portion of Fig. 88. This cold air dam results in the formation of a cold lake every night in the acute angle between the older plantings and changes the cultivated area into a frost flat.

In order to find out the temperatures to which the plants were there subjected at night, thermometers were placed 5 cm above the ground at the points indicated by the large numerals. This was in the spring of 1925. They showed unexpectedly low temperatures as the summary in the following table indicates.

We can see from these figures what extraordinarily large temperature differences can occur at night between places within the same

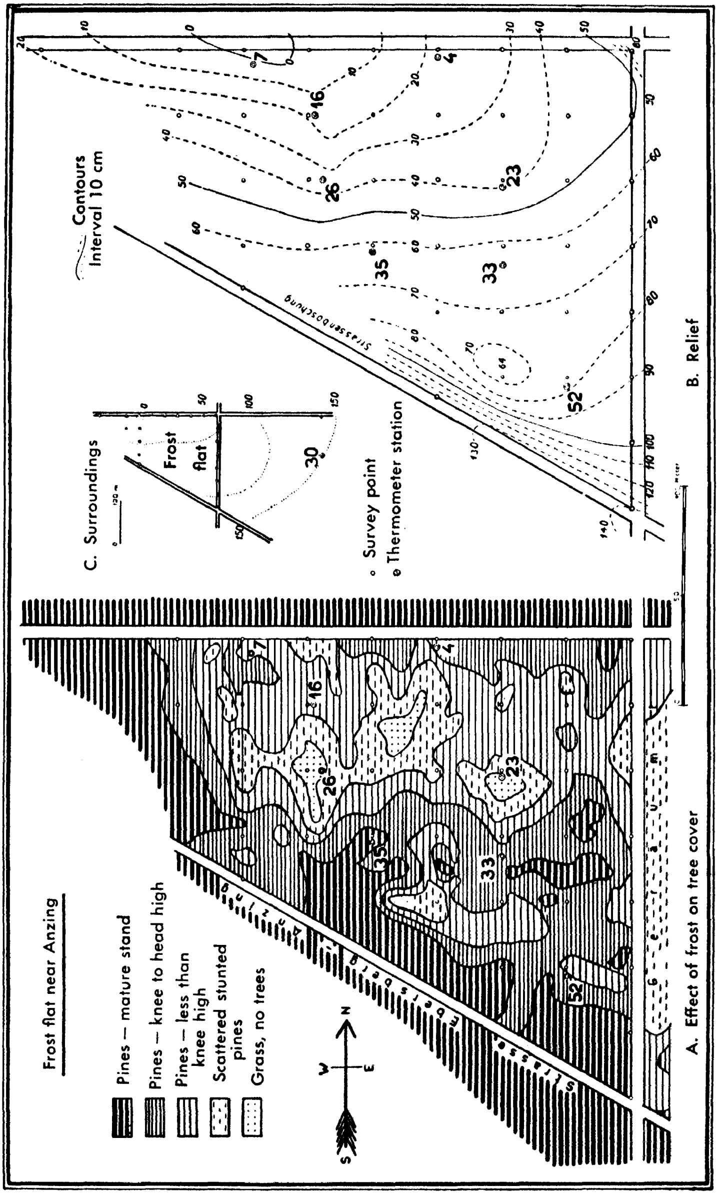

FIG. 88. Result of investigations of late frost in the Anzing Forest near Munich

TABLE 33

Station	Height of Observing Point	May: Mean Temperature	May: Coldest Night 3/4 May	May: Number of frost nights	June: Mean Temperature	June: Coldest Night 7/8 June	June: Number of frost nights
A. For comparison (macroclimate)							
Munich city	8.4 m	8.8	+2.1	0	10.6	+8.2	0
Munich outer station	1.4 m	6.5	−1.8	1	9.0	+4.2	0
B. In the Anzing Forest near Munich							
Anzing pig-sty	5 cm	1.6	− 8.4	12	4.5	−3.9	4
At the frost flat							
Point No. 30	5 cm	0.1	−10.7	17	1.2	−5.2	9
" " 52	5 cm	−0.3	−11.0	17	0.4	−7.9	12
" " 35	5 cm	−0.3	−10.8	19	1.4	−7.1	8
" " 33	5 cm	−0.6	−12.4	20	0.4	−7.0	12
" " 4	5 cm	−0.7	−11.9	20	−0.1	−8.0	14
" " 16	5 cm	−0.8	−12.8	20	0.3	−7.2	13
" " 7	5 cm	−1.1	−13.5	22	0.1	−7.1	13
" " 23	5 cm	−1.5	−13.5	22	−0.2	−7.1	15
" " 26	5 cm	−2.0	−14.4	23	−0.7	−8.8	15

climatic province. In the presence of such low temperatures and such great frost frequency, it is easy to understand why the plants suffered such damage. The effects of freezing, estimated (before temperature observations began) by forest gradations and mapped in the left-hand portion of Fig. 88, agree well with the observed temperatures.

If we consider the relationship between altitude and temperature, we find the greatest cold at the lowest points insofar as such points are not protected by nearby old plantings, such as points 7 and 4. A difference of elevation of the land amounting to only a few centimeters exerts a marked influence on the nocturnal temperature. This differentiation of the low spots is permanent as the monthly mean values show. We must conclude from this that the nocturnal cold air movement occurs with great regularity even when it escapes observation and in spite of the fact that the general weather may be under the domination of such other factors as wind or rain. Numerous observations on the part of forestry and agriculture as to the permanency of cold islands substantiate these facts.

In 1939, R. Geiger and G. Fritzsche (*290*) made some measure-

ments on a frost damaged pine plantation in a teaching district of the Eberwald Forestry College, which led to very similar results. How great here too was the effect of the smallest differences in height is proved by the following results from measurements at five places which lay within a distance of not over 100 m from one another.

TABLE 34

Measuring site no.	8	9	10	11	12
Elevation above sea level (m)	36.1	36.1	36.3	36.6	37.1
Temperature minima (°C)					
Individual frost nights,					
May 23/24, 1939	−7.6	−6.9	−5.4	−5.1	−3.7
June 2/3	−9.4	−7.9	−8.2	−6.7	−5.0
July 2/3	−2.1	−1.3	−1.1	0.0	+0.1
July 11/12	−2.5	−1.4	0.0	+1.6	+1.9
Mean of the 30 coldest nights	−0.6	−0.4	+0.1	+0.7	+1.7

At point 8 there were 17 nights of damaging frost in the spring; at point 12, only 14.

Fig. 89 is a cross-section of a "sink hole," a rock kettle shut in on all sides, resulting from subsidence. It is near Lunz in lower Austria and is called the Gstettneralm (1270 m above sea level). Wilhelm Schmidt (*415*) initiated there a great bioclimatic cooperative project of temperature measurements on the slopes of the sink hole and was able to demonstrate relatively very low night temperatures in the kettle. The cross-section shown in Fig. 89 exaggerates the altitude somewhat. The temperatures which were taken with an Assmann aspiration psychrometer before sunrise on Jan. 21, 1930 are entered at the points of observation. Simultaneous data on wind relationships are given as well. The left side of the illustration gives the section from north-northeast to the middle of the sink hole. On the upper part of the slope for some 70 m down the temperatures are from 1° to 2° below zero. As we descend still further the temperature drops with extraordinary rapidity and on the floor of the kettle reaches −28.8°C. The cold air from the slopes accumulates there and cannot escape. The heavy frost which formed in the lowest 40 m was a visible evidence of this stratification.

In the right hand half of Fig. 89 is a cross-section from the middle toward the west-southwest. Here the sink hole is intersected by a

saddle. Temperatures below freezing prevail up to the height of this saddle. Inasmuch, however, as the cold air can flow over the saddle at this point, the temperatures above the saddle increase rapidly. If we look across at the left half of the illustration we can recognize the effect of this overflow on that side of the sink hole.

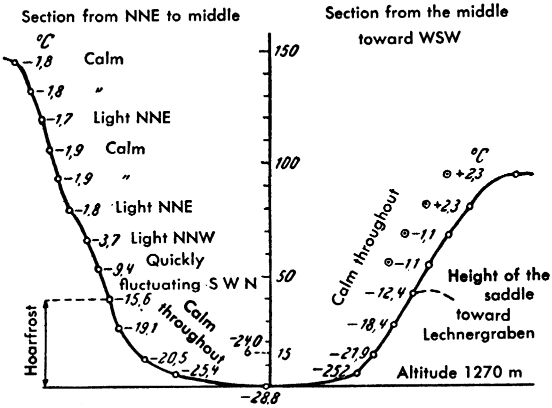

FIG. 89. Temperature distribution in the Gstettneralm sink hole near Lunz on January 21, 1930. (After Wilhelm Schmidt)

The Gstettneralm and Schmidt's measurements have attained fame in that during the well-known severe winter of 1928–29 the lowest minimum temperatures of all middle Europe were observed there, −48°C. A microclimatic phenomenon has here, as so often elsewhere, taken the record away from the macroclimate. It is significant, also, that during the following winters as low as −51° was observed at the same place — an indication that it is not so much the winter weather conditions as a whole, as it is the local, temporary conditions which lead to such extreme temperatures. In the work of W. Schmidt mentioned above, we see in particular the peculiarly conclusive thermogram from the bottom of this sink hole.

Even in midsummer temperatures below freezing are reached in the sink hole, and it is self evident that the plant world and the animal world must adapt themselves to these local conditions. At the bottom of the sink hole the plant growth consists of only a few hardy grasses and a few herbaceous plants which can maintain themselves under protection of the snow cover in winter, while in midsummer they hurry through their growing season in a few weeks. As one ascends the side of the sink hole, knee pines appear first, then stunted pines and snow roses. Farther up the pines be-

come larger and are mingled with alpine roses. At the upper rim of the sink hole is a normal forest. The reversal of normal temperature stratification resulting from the flood of cold air is thus reflected in a reversed plant stratification. Whereas the forest usually ceases as we go upward, it comes to an end here as we descend into the sink hole. Even in the animal world there appears a similar dependence of kind and number of kinds on the relative height in the sink hole. (See Chapter 36.)

F. Innerebner (*457*) has shown, for the meteorological station of Igls, at Innsbruck, that a cold air lake can form even on a slightly inclined plateau "especially at those places where the air is hindered in its flow by apparently insignificant obstacles." The results which were obtained at the macroclimatic stations of the country-wide network may therefore very well be influenced by such cold air accumulations. Even he who is interested only in macroclimatology, will do well to study these phenomena. Yes, a generally accepted fact of macroclimatology can be traced back to such cold air processes: The cold pole of the earth is, according to the recent determination of S. Obrutschew (*408*), no longer Verkhoyansk but Oimekon. This place, like Verkhoyansk, is situated in northeastern Siberia and is surrounded completely by mountain chains. Obrutschew remarks that it forms a "sink most favorable for the formation of a stagnating lake of cold air." There at the macroclimatic station, which is here entirely subject to the action of microclimatic conditions, an air temperature of as low as $-70°C$ has been observed.

We already have learned that nocturnal cold air on account of its thermal stratification, is in a stable condition. If it lies in a sink or kettle, this stability is intensified. At the bottom of cold air lakes a perfect calm prevails. Motionless fog banks often attest to this.

Many will remember when this microclimatic phenomenon cost the lives of not a few people. The general weather conditions during the early days of December, 1930, favored stagnant air and fog formation in the narrow valley of the Maas near Liége to such a degree that the fluorine-bearing waste gases from the zinc and superphosphate factories located there were unusually enriched. Hundreds of people became ill of respiratory complaints, and over 60 died. That this was only an unusual intensification of a normal microclimatic condition may be seen from the fact that in 1911 there was also much harm done in the same area. (See references *393*, *394*, *399*, *401*.)

Up to this point we have only indirectly deduced the facts of

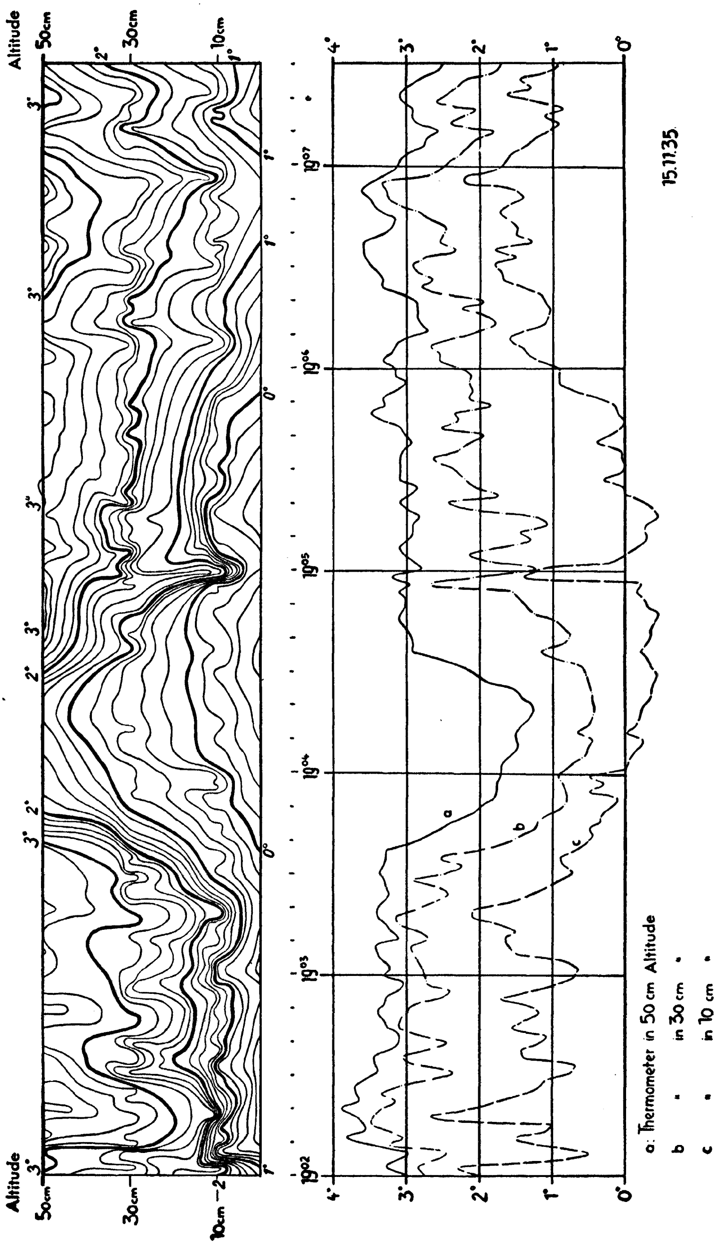

FIG. 90. Measurement of nocturnal drop of cold air by temperature recordings taken at short intervals during its passage past an observation point. (After M. Reiher)

cold air movement from their effect on nocturnal temperature distribution. Just how does this movement take place?

Wilh. Schmidt (*817*) has investigated the method of flow of cold air by means of wind pressure surfaces (cf. p. 42) in the region of the lower Lunz lake and at Gumpoldskirchen near Vienna. He concludes that the downflow of cold air is to be classed as a quiet, uniform movement which may be considered almost laminar. The lack of turbulence results in wind speed being subjectively underestimated. Such a movement assumes of course that the weather permits a quiet air and that the land is uniform and gently sloping.

On steeper slopes — at inclinations over 1% according to A. Defant (*390*) — the downflow of cold air often occurs by bursts or drops. On this point we have some exceptionally fine studies made at the Geophysical Institute of Göttingen by M. Reiher (*411*). On a steep slope with a 1/3 pitch he placed platinum resistance thermometers at heights of 10, 30 and 50 cm above the bottom. Fig. 90 shows a result of his measurements, which permits us to draw a conclusion from the temperature field as to the nature of the air flow. Time is taken for the abscissa, it amounts to only 5½ minutes. In the lower half, the course of the temperature at the three measuring points, during this period, is represented. Outgoing radiation prevails. It is plainly seen that shortly after 7:04 P.M. a "drop" of cold air passes the station. The temperature stratification above the ground, as a function of time, is shown in the upper half of the figure. We can readily imagine that this picture also shows the form of the air mass passing the measuring point. It flows from right to left. In the middle we recognize the highly arched drop of cold air. It pushes forward a tongue which raises the passive warm air previously on the ground. This we learn from the compression of the isotherms above the cold air (at 7:02 P.M.). After passage of the cold air drop, at about 7:07, warm air again occupies the lowest half meter above the ground.

This dropping of cold air was repeated rhythmically every 4 or 5 minutes, in the case under observation. The speed of flow of the cold air was 1.4 m per sec; the length of the cold air mass, about 300 to 400 m.

CHAPTER 19

Nocturnal Temperature Relationships in Valleys

Cold air floods and cold air dams, as described in the preceding chapter, were of small dimensions. Cold air movement gains significance when it occurs in great volume. This is the case in valleys. The present chapter will be devoted to the description of such conditions, while the one following will take up the "down-valley" wind.

First let us return for a moment to the explanation of cold air flow. It has been already pointed out that the comparison of cold air movement with that of flowing water is only partially correct. C. F. Marvin (*405*) was probably the first to show clearly the difference between the two processes.

In contrast to water, air is a compressible medium. In up and down movements, consequently, there is always a question whether the change of state of the air, due to this displacement, is of significance. For air which sinks on account of its weight is dynamically heated (foehn) while rising air experiences cooling. To be sure, this, if it is to be practically effective, assumes quite large vertical displacements and adiabatically controlled changes. The first assumption is seldom fulfilled by the slow, gentle movements of cold air; the latter, never.

In the second place, the energy of air movement — on account of air being a thousand times less dense than water — is very small. If we assume with M. Reiher (*411*) that cold air flow occurs only under the influence of gravity, then the velocity of flow V in m per sec is obtained from the expression

$$V = \sqrt{2g'h}$$

where g' is the downward acceleration acting on the air mass and h is the distance of fall. If T is the absolute temperature of the cold air, T' that of the surrounding air, and g the normal acceleration due to gravity (981 cm/sec^2) then

$$g' = \frac{T - T'}{T'} \cdot g$$

In his experiments M. Reiher found that the equation was confirmed in general by the results of his investigations. As mentioned above, he had measured a velocity of 1.4 m per sec. G. S. P. Heywood (*397*) found, from measurements in the English Cotswold Hills, speeds of from 1.2 m to 1.6 m per sec. Using probable values for T and T' we always get similar experimentally justified values for cold air movement in flat or hilly country. (Chapter 20 will cover the more extensive "cold air winds" which attain considerably higher velocities.)

Finally, water movement and cold air movement differ in this, that a space can be empty of water but cannot be empty of air. Cold air movement consequently is the beginning of a circulation between cold and warmer air and only the initiation of such a circulation can keep the cold air in movement very long.

The last difference is clearly visible when we study the nocturnal temperature stratification in a valley.

Fig. 91 shows diagrammatically the cross-section of a valley. On the plateau, sections of which are shown to the right and left, along the valley walls and on its floor, the lower air cools off at night at the same time as the ground surface. If the air behaved like water, there would have to be a circulation like that at the upper left of Fig. 91 and the temperature distribution would be arranged in horizontal layers according to density as shown at the upper right. Such a simple circulation does not develop however. On the contrary, a series of smaller circulations form on the slopes. In these, the cold air on the slopes is mixed with the neighboring warm air, of which there is a great reservoir between the valley walls, as shown at the lower left. On the floor of the valley cold air accumulates. The cold lake which forms there is deepened by the adjacent circulation on the slope. The intermediate condition depicted on the slopes reaches even to the edges of the plateau. The resultant temperature distribution is shown at the lower right of Fig. 91.

The plateau is cold and the valley floor, very cold, but the higher part of the side slopes are warm. We speak therefore of a warm slope (thermal belt). It is the safest place in areas and at times where there is danger of frost. It is often indicated by the vegetation.

F. W. Nitze (*407*) was able to make a direct observation of the nocturnal circulation shown at the lower left of Fig. 91. Small rubber balloons, which were carried with the drifting air without upward lift, carried little lights at their lower ends. The light from these lamps traced the course of the balloons on the sensitive plates of a stereophotogrammetric measuring apparatus. In this way it was

possible to determine accurately the course of nocturnal air circulation. Such pilot balloons were released at various places on a rather steep slope and their course showed the equalizing movement which was taking place between the cold air on the slope and the heat reservoir.

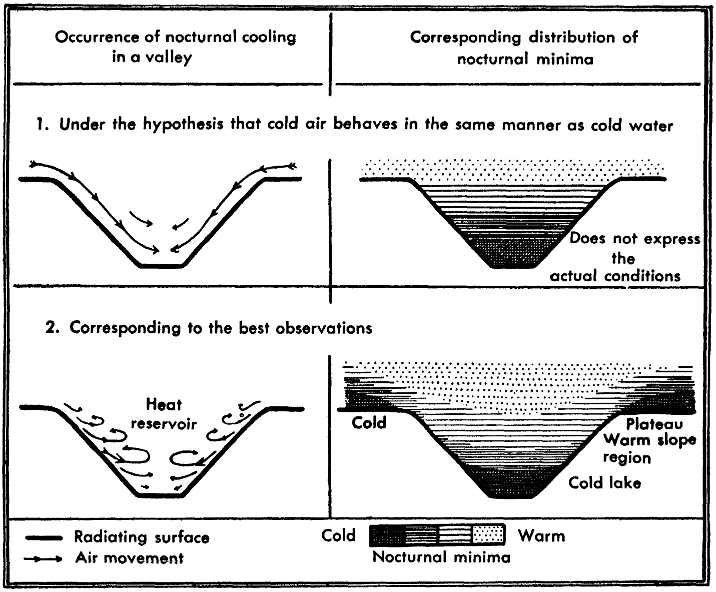

FIG. 91. Schematic representation of the origin of the warm slope zone [thermal belt]

The temperature distribution over the valley cross-section is confirmed by observations. In a valley in Oregon, U.S.A., there was a radio tower about 100 m high near the middle of the valley. F. D. Young (*423*) in 1918 made temperature measurements along the sides of the valley, and on the radio tower. As an average of 32 nights in April and May he found the temperature distribution represented in Fig. 92. It corresponds in general to the condition shown at the lower right of Fig. 91.

The height at which the warm thermal belt is found, depends on the time and the locality.

As the cold air gathers at the bottom of the valley the warm thermal belt in the course of the evening moves upward. Fig. 93 shows the result of the measurements of Wilh. Schmidt (*466*) on a

microclimatic experimental field situated on the eastern slope of the Vienna forest at Gumpoldskirchen. Several observation stations were distributed along the slope. Fig. 93 gives the temperatures at three different times during the night of a late frost on the 11–12th

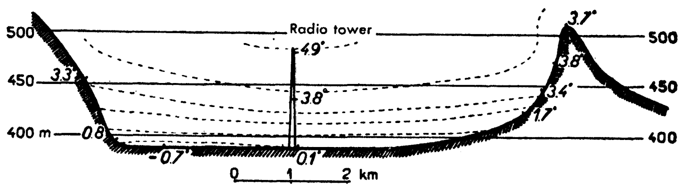

FIG. 92. Nocturnal temperatures in a valley near Medford, Ore. (After F. D. Young)

of May, 1928. About 8:12 P.M. the temperature of the air on the bottom of the valley has already retreated to nearly 2°, while at 240 m msl on the slope it is still almost 7°. In the course of the night the whole temperature curve corresponding to the continued cooling moves toward the left on the chart. Through the influx of cold air

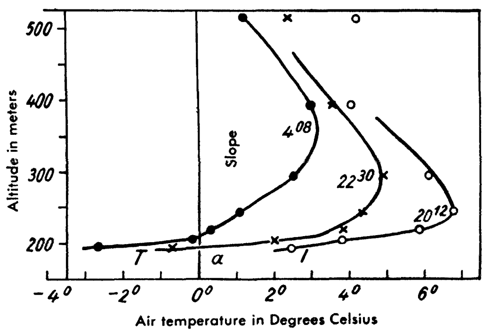

FIG. 93. Nocturnal upward migration of the warmest zone on a slope at Gumpoldskirchen near Vienna. (After Wilh. Schmidt)

on the valley floor the most favorable zone recedes at about 10:30 P.M. to a height of some 300 m, and at about 4:08 A.M. to around 350 m. In the lowest part there is a heavy frost during these early morning hours, although the warm thermal zone enjoys the advantage of a +3° temperature.

At any given place this upward migration of the temperature maximum goes on to a certain extent every clear night. Although there are certain differences in individual cases, depending on

weather conditions, yet over a long period the thermal zone has an average height at the end of the night, which is the time of the temperature minimum. The vegetation is adjusted to this average position.

R. Geiger, M. Woelfle, and L. Ph. Seip (455) in the springs of 1931 and 1932 studied these relationships on the slopes of the Gross Arber in the Bavarian forest. Twenty-three measuring points for the determination of minimum temperature were set up at heights between 639 and 895 m msl on the side slopes of the great Regenfluss near the "Seebach slide." The left half of Fig. 94 shows a cross-section of the slope; the points of observation are indicated by small vertical strokes.

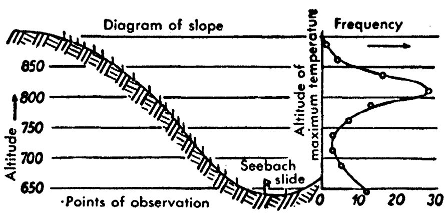

FIG. 94. Position of the warm slope zone. (After R. Geiger, M. Woelfle, and L. Ph. Seip)

The right half of the figure contains a frequency curve showing what heights the thermal zone attained. There is a weak frequency maximum at the bottom of the valley. When the warmest temperature occurs below, it means that the nocturnal temperature decreases steadily upward. This is the case when in very stormy, and particularly in rainy weather there is no true thermal stratification in the valley. This situation does not interest us here. On the other hand it is readily seen that the thermal zone is normally over 800 m and that it fluctuates only slightly up and down.

In the case we are considering, beeches are found at just above this height while both above and below they are always frozen back by late spring frosts. In order to establish still better the influence of microclimatic temperatures in the plant world, simultaneous phenologic observations were carried on by the authors. Fig. 95 illustrates the results obtained. At the left we have the change of nocturnal minima with height. At each measuring point the average of 68 May and June nights in 1931–32 is entered. Not only clear radiation nights were used, but all available data. The thermal zone between 800 and 850 m is very evident.

On the right hand side of Fig. 95, the phenological observations are reproduced. For better comparison with the temperature curve the time is drawn consecutively from right to left. Early budding and high night temperatures therefore lie further to the right than late plant development and lower temperatures. The similarity between the phenologic and the temperature curves is striking; the thermal zone is preferred in each.

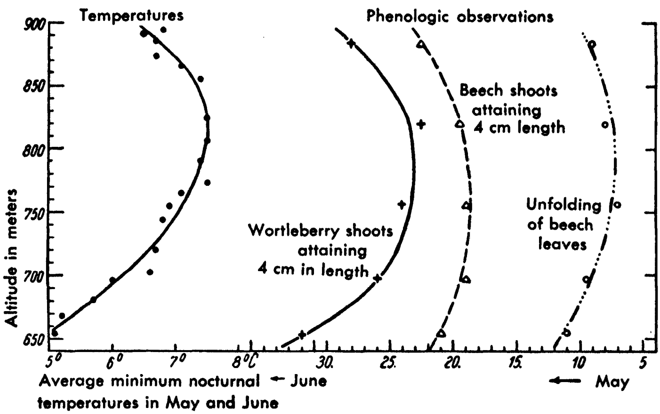

FIG. 95. Relation between nocturnal temperatures (left) and plant growth (right) on a slope in the Bavarian Forest.

Fig. 96 shows how the nocturnal fall of temperature proceeds at the various points along the valley slopes. It represents the course of temperature during the night of Dec. 27–28, 1918 on the slopes of San José mountain in the Pomona valley (California, U. S. A.). The thermogram was published by F. D. Young (*423*). The temperature increases up to a height of 68 m. The record at a height of 84 m, however, already shows lower temperatures, an indication that the thermal zone has been passed. It should be particularly noted, that at the two lowest stations the temperature curve is almost horizontal just before sunrise. The cold air is firmly anchored to the valley floor, while higher up the slope the small circulation currents make the course of the temperature uneven.

Under favorable circumstances the nocturnal temperature distribution over the country, which we have been able to demonstrate as a result of special investigations, can be observed directly. Hoarfrost, rime or snow render the microclimatic zones of elevation visible. They are most easily recognized when fog fills the cold

hollows and valleys. We may read the lively description which C. F. Brooks (*475*) gave of an early morning auto ride from Cape Cod, on the eastern coast of the United States, toward the interior of Massachusetts. "Light fog," he writes, among other remarks, "was to be seen here and there in shallow basins. While it did not hinder the driving, yet every time the auto passed from a colder

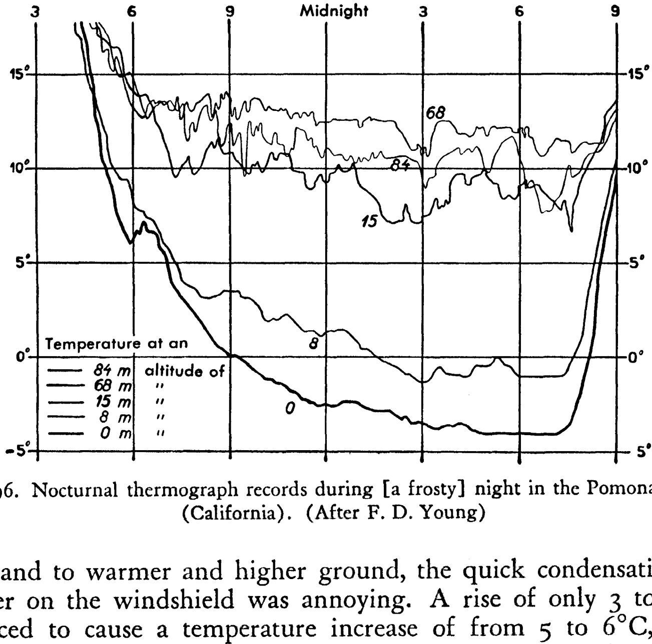

Fig. 96. Nocturnal thermograph records during [a frosty] night in the Pomona valley (California). (After F. D. Young)

lowland to warmer and higher ground, the quick condensation of water on the windshield was annoying. A rise of only 3 to 6 m sufficed to cause a temperature increase of from 5 to 6°C, thus causing a thick deposit in the form of drops on both sides of the windshield." W. Malsch (*403*) has recently described a similar instance. While passing through an inversion in a valley of the Bavarian forest, the windshield of his open auto suddenly iced over to such a degree that it was impossible to see through it and a stop had to be made to clean it off. Thus does the microclimate at times enter directly into our everyday life.

CHAPTER 20

Cold Air Winds

Down-slope, Down-valley, and Glacier Winds

In Chapter 18 we recognized a cold air stream as slow, nocturnal air movement at a speed of from 1 to 1½ m per sec. In a large valley this movement results not only from outward radiation from the valley floor but the radiating side slopes also have cold air layers close to the ground, which flow downward and hence are called "(nocturnal) down-slope" winds. From these down-slope winds there develops the *down-valley* wind which, under the formerly used designation of "mountain wind," is one of the best-known diurnal periodic winds described in meteorological text books. It is a wind of local occurrence and to a great extent determines the microclimate of the region affected by it.

A. Wagner (*420*), in cooperation with his school of meteorology at Innsbruck, during the 1930's published a great number of valuable papers giving a new and complete picture of periodic mountain winds. Fig. 97 is taken from his summarizing work of

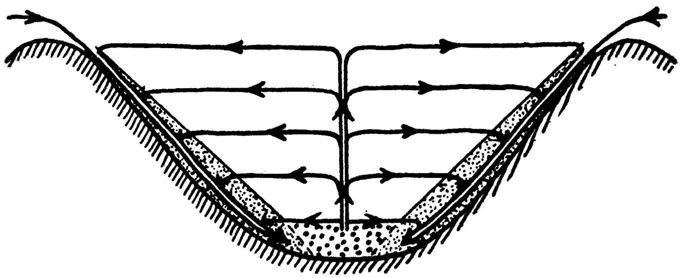

FIG. 97. A. Wagner's explanation of the nocturnal down-valley winds

1938. It represents diagrammatically the normal circulation in valleys at night. The finely dotted area indicates the region of down-slope winds which have potential energy with respect to the valley floor and which are fed from the central reservoir of heat. The coarsely dotted area represents the region of down-valley wind which we are to imagine as flowing at right angles to the plane of the illustration. It is made up of two parts, differing in origin. The

one is a down-slope wind all along the valley floor, which is fed from the side slopes; the other is a wind resulting from the pressure difference between mountain and plain just as the ocean breeze in its macroclimatic scope is dependent on the contrast of sea and land.

Thus the large-scale down-valley wind results from small-scale cold air streams. Its velocity may be more than 1.5 m per sec which we have set as the upper limit for cold air streams. In vertical extent it sometimes builds up to several hundred meters.

As an example we cite the "Wisper wind" which has been carefully studied by H. Schultz (*416*).

In the Wisper valley, which opens into the Rhine from the east at Lorch, a down-valley wind sets in with great regularity in the evening shortly after darkness comes. This wind attains a velocity of 3, or sometimes even 4, m per sec. It represents the downflow of nocturnal cold air out of the cool Wisper valley into the relatively warmer main valley of the Rhine. It is stronger, the clearer the night and the weaker the gradient wind (i.e. wind resulting from pressure gradient). The Wisper wind decreases in strength with elevation and has a depth of 100 to 150 m in all.

H. Schultz was able to show in addition that the velocity of the Wisper wind increases in direct relation to the magnitude of the nocturnal temperature inversion in the Wisper valley — a proof that the local wind is governed by local temperature contrasts. Since the night temperatures in turn depend on cloudiness, there followed an increase of wind speed with decrease of cloudiness.

In a similar manner, R. Luft (*402*), analyzing 18 years of observations at Bonn on the left bank of the Rhine and Beuel on the right bank, proved the significance of the "seven-mountain wind" in the local climate. L. Schulz (*417*) studied the down-valley wind at the Braunlage sanitarium in the upper Harz.

In mountainous country the downflow of cold air can, under certain conditions, be at first dammed and then suddenly loosed so that it rushes violently down in what A. Schmauss (*414*) has aptly termed an "air avalanche." He discovered the phenomenon in the German Alps and has described it more fully. Such downrushes of cold-air bodies have also been observed in the high mountains of central Africa — by H. Scaëtta (*412, 413*), for instance, at Karisimbi (4,000 m) northeast of Lake Kiwu. He reports a case when his tent was almost carried away by such an evening air avalanche. The same kind of a storm was repeated on succeeding evenings at the same hour, although with less violence — a further indication that it was a daily periodic phenomenon.

We must here mention a particular wind which is also a cold air stream, though not a result of nocturnal radiation—the glacier wind, or "firn-wind." The air close to a glacier is in summer cooled by the glacier ice far below the temperature of its surroundings and begins to move downward in the same direction as the glacier. The hotter the summer and the finer the weather, the more this wind is developed, as H. Tollner (*419*) has shown in the first thorough

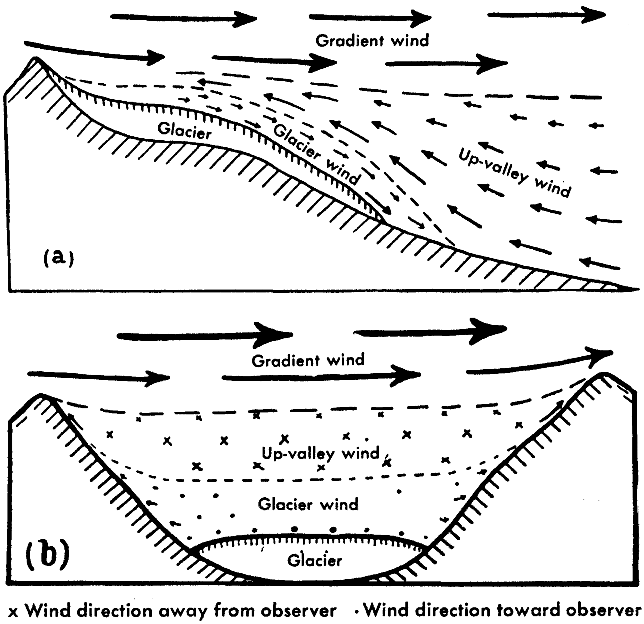

FIG. 98. Arrangements of glacier winds in the mountain wind system during the day. (After E. Ekhart)

description of this process. While the usual cold-air stream is a night wind, however, the glacier wind is a day wind. Both are fair weather winds.

E. Ekhart (*392*), using pilot balloons on the Hintereis and Gepatschferner glaciers in the Ötz valley has made a thorough investigation of the nature of the glacier wind. In summer it begins at about 8 or 9 A.M. and is at first a gentle current only a few meters deep. It grows rapidly in depth and strength to a depth of 200 to 300 m and a speed, near the ground, of 4 to 5 m per sec. The steep

slope of the glacier favors high speed and a considerable gustiness as well. The greatest velocity is found at a height of about 2 m above the ice. Below this, the friction causes it to diminish rapidly. It also diminishes upward, being at 50 m only half its maximum value and at 120 m only a quarter thereof. Even when most fully developed, the glacier wind does not extend far down valley beyond the front of the ice, but it causes a marked drop in temperature within the area it reaches. Toward evening this wind declines in strength and depth, dying out at about 8 P.M.

Fig. 98 is a diagram of the glacier wind as E. Ekhart has given it to us from his experience. It shows in the upper part a longitudinal section of wind relationships on a summer midday, and, in the lower part, a cross-section of the valley. The length of the arrows and the size of the crosses and points indicate the relative magnitude of the wind speeds involved.

Strongest of all is the upper, gradient wind resulting from the pressure gradient. This has nothing to do with the local fair-weather winds and so does not interest us here. The mountain valley is filled at the assumed midday hour with an up-valley wind with which we shall not become acquainted till later. It pushes over the downward flowing glacier wind. The observationally confirmed fact should be noted, that the glacier wind directly over the middle of the glacier is shallower than along the mountain slopes. (See the cross-section.) E. Ekhart explains this through divergence which must develop above the heaped up center of the glacier and forces the air sideways toward the slopes. A further cause is the greater friction along the slopes, which allows the air at the center to flow away more easily.

Since the glacier wind is a true cold air wind it has been treated here in connection with down-slope and down-valley winds. As a daytime wind, however, it belongs in the following chapter, in which we begin to investigate the influence of topography by *day* on the nature of local climates.

CHAPTER 21

The Sunniness of Different Slopes

During the day topography has a great effect on climate in that the sun delivers different quantities of heat to sloping and flat ground. To what degree the sloping ground or hillside is favored or the contrary, depends on the direction and inclination of slope. Together, these constitute the exposure. When these two factors are known, together with radiation intensity on a surface at right angles to the insolation (the so called "full radiation [1]), or that on a flat surface (so called "horizontal radiation") the radiation on the slope can be calculated.

Differential sunning has such a great effect on climate that it was this meaning that the ancient Greeks attributed to the "climate." For climate is of course derived from κλινειν, to slope. *Side-hill* climate, or *exposure* climate was to them merely *the* climate. Today, as then, it has the greatest practical significance for many questions of agriculture, forestry, gardening and other technical occupations. Since it is now relatively easy to determine the insolation on different slopes, there are a number of works on the subject. The amount of radiation received depends on five factors — i.e. the time of day, the season, the degree of cloudiness, the direction of slope, and the angle of slope. In addition, we now ask for momentary values of radiation, again for totals for days, months or for longer periods of time. There is no one representation which can be used exclusively for all practical purposes. In order to help the reader to find what he requires, we must first glance over the computations which have been made.

There is just one work — that of J. von Kienle (*429*) — which is devoted to a calculation of the *duration* of sunshine on different slopes; all the others are concerned with radiation intensity. Of the latter, two are based chiefly on theoretical considerations, proceeding from astronomical calculations; these are the works of R. Gessler (*426*) and M. R. Pers (*432*). Four other publications are based on actual measurements of radiation intensity, and consequently are of

[1] The concept of *full radiation* is not to be confused with that of the *total radiation* (radiation from sun and sky together) nor with that of the *sum of radiations* (solar radiation summed over all wave lengths), which will be made use of in the following pages.

TABLE 35

Groups		Author and year of publication	Calculated for latitude ϕ	Angles and directions of slope considered	Times covered	Quantities calculated	Form of results
Duration		J. v. Kienle 1933	49°	0, 15, 30, 45, 60, 75, 90 N, NE, E, SE, S, SW, W, NW	1. All months 2. Summer and winter 3. Year	1. Time of sunrise and sunset 2. Astronomical possibility 3. Actually available (2., 3.) Sunshine duration a) in hours b) in % of values on a plain	Tables
Intensity of solar radiation	On theoretical grounds	R. Gessler 1925	0, 15, 30, 45, 60, 75, 90	0, 15, 30, 45, 90, N, NE = NW, E, SE = SW, S	1. 17 selected days 2. Seasons 3. Year	Insolation without regard to the influence of the atmosphere	Tables
		M. R. Pers 1935	45°	0, 30, 90, E = W, SE = SW, S	9 selected days in the year	Daily course of radiation intensity (graphic), assuming a transmission coefficient of 0.8	Displays (heliocycles)

Intensity of solar radiation	On the basis of measurements of radiation	G. Perl 1936	0, 15, 30, 45, 60, 75, 90	0, 90 N = S, E = W	1. Daily course for 4 selected days 2. Totals from sunrise to a stated hour	1. Irradiation intensity 2. Total irradiation, derived from measurements at 80 sites	Tables and graphs
		H. H. Kimball and I. F. Hand 1922	42°	0, 90 N, NE, E, SE, S, SW, W, NW	All months	1. Radiation from cloudy sky 2. Radiation from clear sky 3. Radiation from sun and sky	Graphs
				0, 10,20,30 N, NE, S, SW, SE		1. Radiation from sky 2. Radiation from sun and sky	Table
		W. Schmidt 1926	48°	0, 30, 90 N, E, S, W	4 selected days (Jan. 1, Apr. 1, July 1, Oct. 1)	Radiation intensity	Graphs
		J. Schubert 1928	52°	0, 30, 90 N, E, S, W	All months (Hourly values and totals for the middle day of the month)	1. Radiation intensity 2. Daily total of radiation a) clear days b) days with average cloudiness	Tables and graphs

particularly practical importance. Of these, G. Perl (*431*) considered all latitudes in working over the radiation data from 80 different parts of the earth. For individual locations within the range of our climate, computations have been made by H. H. Kimball and I. F. Hand (*430*) for Washington in 1922, by W. Schmidt (*433*) for Vienna in 1926, and by J. Schubert (*39*) for Potsdam in 1928. C. Schoy (*434*) has studied radiation received by mountains of different shapes. In the accompanying table we submit to the reader a survey of what is to be found in the works mentioned.

In calculations of this sort there is usually something left out which is nevertheless of great importance in their practical application.

The amount of heat which a slope receives is made up of two parts—direct insolation and diffuse sky radiation. The former varies with the direction and angle of slope; the latter with angle only. A 20° north slope receives just as much diffuse radiation as a 20° south slope and the amounts of heat received by each do not differ greatly from that falling on a horizontal surface. Sky radiation, therefore, moderates differences of exposure. The greater the ratio of diffuse sky radiation to total radiation, the more are the differences between various slopes effaced.

It follows from this that large differences in exposure will be encountered in clear weather, small differences in overcast weather. Fig. 99 furnishes a proof of this. In 1926 R. Geiger (*454*) made a

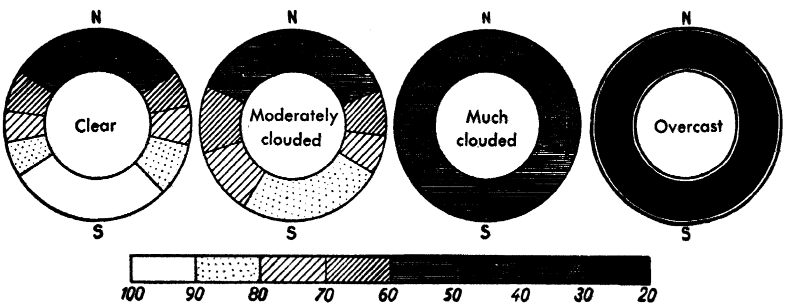

FIG. 99. Influence of cloudiness on the irradiation of a slope. (After measurements on the Hohenkarpfen, 1926)

series of observations on the Hohenkarpfen, a symmetrically round mountain cone of the Swabian Alps. He mounted Eder-Hecht optical wedge photometers toward the eight main points of the compass—all inclined 35°, which corresponded to the average

slope of the mountain. From the average of 116 days of observations, which were divided into four groups, according to the degree of cloudiness, he obtained the percentage distribution of light falling on the slopes, which is represented in Fig. 99. The amount which fell on the south slope in clear weather was taken as 100%.

As the figure shows, the amount of light decreases with increase of cloudiness. With an entirely clouded sky, it is, for all directions of slope, between 1/4 and 1/5 of that falling on a south slope on clear days. As cloudiness increases, the difference of slope direction, which is in general symmetrical with respect to the north and south axis, decreases. In clear weather the difference between north and south exposures amounts to 46 units; with a clouded sky, to only 2.

In the investigation referred to, this law was at first established only for the short wave radiation to which the optical wedge photometers are sensitive. We can assume, however, that it holds for total radiation as well.

In addition to the law of the influence of cloudiness on the difference-of-exposure, there is the influence of latitude.

In those tropical regions where the sun stands in the zenith, the differences due to direction of slope are small; at midday they disappear entirely; there are no sunny and shady sides. Consequently, in those very regions which have the strongest insolation, the difference of exposure is least important to climate. In the far north, on the other hand, where the position of the sun occasions the greatest differences, the ratio of direct to diffuse radiation is relatively small. Equalizing diffuse radiation predominates, and the total radiation is not great. The consequence is that in polar regions, also, the matter of exposure is not as significant for plants, man or beast as right in our own middle latitudes.

As we ascend a mountain the radiation increases, while the air temperature decreases. The importance of climatic differences resulting from different amounts of radiation received on slopes of various exposure, therefore, increases with altitude. In the Alps, north slopes and south slopes are two fundamentally different habitats for all life dependent on the sun. At a certain time in the spring when everything is dormant on the snowcovered north slopes, the first flowers are in bloom on the south slopes between banks of melting snow or even under them. It is no wonder, then, that it was in the mountains that climatic variation according to slope was first noticed and first studied.

Let us now consider the amounts of radiation, corresponding to

our latitude, which the slopes of various inclination and direction receive.

We use for this purpose the computations of W. Kaempfert, (*426b*) (published 1942) for Trier (49°45′N) which are based on radiation observations of the years 1930–33 and were made with regard to practical agrarian-meteorological requirements. We can deduce the fundamental laws from Fig. 100; it gives also immediate answers to all practical problems, at least as far as the order of magnitude of the amounts of radiation in question is concerned.

In Fig. 100 the time is plotted on the ordinate in true solar time, the angle of inclination of the slope in degrees on the abscissa. In nine separate figures are shown the maxima of sun radiation which can be expected with cloudless sky and normal turbidity of the atmosphere, in gcal/sq cm hr related to the surface of the slope. These values are based on the measurements on the Petersberg near Trier (267 m altitude); there, the normal turbidity corresponded approximately to the turbidity factor 3, i.e. pure country air. (The turbidity factor equals the number of ideally pure dry atmospheres which would cause the equal depletion of sun radiation as the observed real atmosphere.)

The three figures on the left side concern June 21; those of the middle series are valid for the 21st of March (approximately also for the 23rd of September); those at the right side for December 21. The three figures in the upper series are valid for the northern slope; those in the middle are for the east slope; (if forenoon and afternoon are exchanged one for the other also for the west slope); those of the lower part of the picture are valid for the southern slope. In each individual figure slopes are considered starting from 0° (plain) up to 90° (vertical wall). The left side of each individual figure represents therefore the radiation upon the plain; consequently, it is the same for each of the three pictures one below the other, regarding the daily duration of sunshine as well as for the lines of equal intensity of radiation starting from the left side. The right boundary of each individual figure corresponds with the radiation upon the vertical wall. The upper border corresponds with the time of sunrise the lower with that of sunset. Symmetry to the noon line naturally exists for the northern and the southern slope, not for the east slope.

Let us start with the lower series, the southern slope. On the 21st of March (in the middle) when the sun rises exactly in the east and sets exactly in the west, as well as during the entire winter half year (right-side figure) the sun appears on the southern slopes of all inclinations in the same moment, namely when it rises up above the

horizon. In the morning of the summer half year, however, the sun needs the more time the steeper the southern slope is, to move from its northeastern azimuth towards the east point and to rise so high that it strikes the southern slope. The upper and lower border lines are, therefore, curved in the left figure, and are almost straight

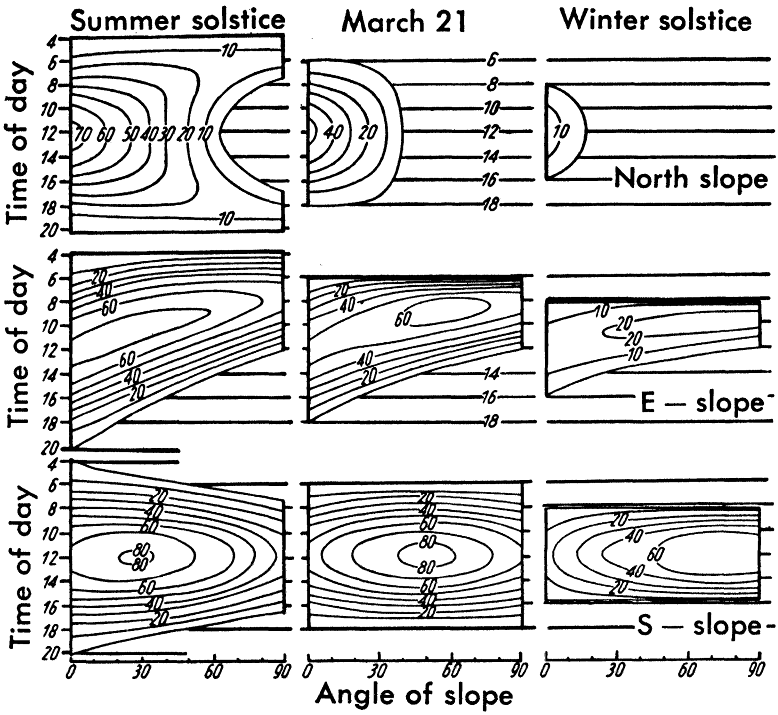

FIG. 100. Maximum amounts of insolation in Trier for N-, E(W)- and S-slopes of all inclinations for three selected days. (After calculations of W. Kaempfert)

in the middle and right figures. The intensity, always greatest at noon, is the greatest on that slope which is perpendicular to the sun. The maximum is, therefore, shifted from the flatter slope in the summer when the sun is high (left) to the steeper slope, in the winter when the sun is low (right). December 21, at noon, the southern wall receives a radiation intensity which is received by the plain only after 9 A.M. at summer solstice. We shall come back to this practically important fact.

First, we consider the northern slope in the upper row of Fig. 100. In the mid-summer (left) time of sunrise and sunset are identical for all slope inclinations. If the slope is very steep, however, the sun at noon, standing in the south, does not reach it; therefore, the right border shows the remarkable "collar-yoke." On the steep northern slope, sunshine exists only in the early morning and late evening hours. For most northern slopes, the maximum intensity occurs at noon, the same as with the southern slope; but in contradiction to the southern slope the maximum intensity of the northern slope occurs at the inclination 0° (the plain).

The eastern slope (middle row) is distinguished from the northern and southern slope in that the time of peak intensity of the incident radiation varies according to inclination and season. Also here, similar to the southern slope, the shifting from flatter slopes in summer to steeper ones in winter can be recognized. Sunrise is invariable for all inclinations, sunset occurs the earlier the steeper the slope is.

It is up to the reader to plunge into the figure more and more and to interpolate between the selected extreme seasons and the slope directions, for example the southeast slope.

The inclination of the slope is represented, in Fig. 100, in degrees of angle and is often wrongly estimated. A lawn of 10° inclination is often estimated as very steep. In the high mountains an alpine pasture reaches rarely more than 25° inclination. Greater inclinations occur practically only with rocky slopes and buildings. Gradient and angle of inclination are correlated this way:

Gradient:	1:500	1:100	1:50	1:20	1:10	1:5
Inclination (°)	0.1	0.6	1.1	2.9	5.7	11.3

The angle of 90° becomes an important factor when the indoor climate and plants trained on trellis-work are taken into consideration. W. Kaempfert (*426c*) published a special study about the sun radiation on walls covered with trellis work facing the south.

As a supplement to Fig. 100 the following table, computed by J. Schubert (*39*), may serve. In contradistinction to Fig. 100 allowance is here made for the average cloudiness conditions and, moreover, the *daily amounts* are given for all months. The radiation measurements of 27 years at Potsdam (52° 23′N) are used in this paper.

From the amounts of radiation for vertical walls we find that in midsummer the east side of a house is most favored. Compared with a horizontal surface, an east or west wall receives less heat throughout the whole year, while a south wall, from Sept. through

TABLE 36

DAILY SUM OF SOLAR RADIATION IN CAL/CM^2 FOR THE MEAN DAY OF THE MONTH ON THE BASIS OF RADIATION MEASUREMENTS 1907–1923 COMPUTED UNDER THE ASSUMPTION OF MEAN CLOUDINESS (see text) BY JOH. SCHUBERT (1928)

Total Radiation on	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
A horizontal surface	20	44	102	196	276	319	269	223	165	81	25	15
A south slope of 30°	54	91	161	248	303	326	283	263	235	149	63	45
" east " " "	18	42	96	182	251	289	240	204	153	76	24	14
" west " " "	19	42	92	175	245	281	239	198	149	76	25	15
" north " " "	..	..	15	91	176	228	183	124	50	..	..	..
A south facing wall	74	106	146	158	136	120	113	143	184	157	82	65
" east " "	13	29	61	106	133	148	122	112	91	49	17	10
" west " "	14	29	56	99	126	139	121	106	88	49	18	12
" north " "	..	..	..	1	11	23	14	4	0	..	..	..

March, receives more. The highest totals of radiation falling on vertical walls occur in early spring and late autumn on a south wall. This explains early flowering on south walls. (Compare Chapter 35.)

J. Schubert has computed the amounts of heat received by slopes and walls on a clear day in the middle of May, the month which is of prime importance in plant development. The following daily amounts in cal per sq cm are arranged in preferred order.

(For comparison, full radiation, that is, the radiation on a surface which is continuously perpendicular to the sun's rays = 916).

South slope, inclined 23½°	594
South slope, inclined 30°	591
Horizontal surface	547
East or west slope, inclined 30°	500
South slope inclined 60°	486
North slope inclined 30°	361
An east or west wall	278
A south wall	264
A north wall	39

The varied sunning of different slopes affects ground temperatures, primarily. Unfortunately we have few measurements of this effect.

As far back as 1878, E. Wollny (*435*) prepared, in a garden, eight areas of sifted soil which sloped at a 15° inclination toward the eight main directions. He took temperatures three times a day (7:30 A.M., noon, 5:30 P.M.) at a point 15 cm beneath the surface. The average temperatures for the most important months were:

TABLE 37

DIRECTION OF SLOPE

Month	N	NE	E	SE	S	SW	W	NW
May	10.7	10.9	11.2	11.4	11.3	11.3	11.0	10.9
June	20.4	20.6	20.8	21.4	21.4	21.4	20.9	20.6
July	18.7	18.9	19.1	19.4	19.3	19.2	18.9	18.7
August	19.2	19.4	19.8	20.4	20.5	20.5	19.9	19.4
September	12.3	12.5	13.2	13.7	13.9	13.7	13.2	12.7

South or southeast slopes appear warmest. We shall soon discuss the reason. A. Bühler (*424*) in 1895 made similar studies at Adlisberg in Switzerland but considered only four directions of slope.

We have the open country measurements of A. Kerner (*427, 428*), carried out at Judenbüchel near Innsbruck from 1887 through 1890. They were made, however, not on the ground but at the considerable depth of 70 to 80 cm. Nevertheless on account of the close relation between surface and ground temperatures they are of some assistance to us.

The results of Kerner's measurements are represented in Fig. 101 in a modified way (*461*). The circular form of the figure may support the idea of the direction of the slope. The concentric circles correspond with the months. For each month the temperature of the ground is calculated as the average of all directions. The difference between the individual temperatures of the slopes and this average is plotted on Fig. 101. The hatched negative portions are relatively cold, the dotted positive are relatively warm.

The maximum temperature differences between the separate directions of slope occur in the summer (at the center of the circular surface), in opposition to the theoretical figures of Gessler, which did not consider the weakening of radiation in the atmosphere.

The coldest direction of slope, as might be expected, is the northern. The warmest direction varies, however, in the course of the year. From January till spring the temperature maximum lies in the southwest: then it moves quickly toward the southeast where it is found in June. During summer and autumn it completes the cycle back to the southwest. This phenomenon which we also found in the previously quoted measurements of E. Wollny, may be explained as follows:—

The ground temperature depends not only on the intensity of insolation, but also on the condition of the ground—particularly on its highly variable moisture content. The morning sun finds a moist ground. A great part of the solar energy radiated during the forenoon is therefore used up in evaporation with a drying out effect on the soil. But when in the afternoon the sun does its greatest work on the southwestern slopes of the mountain the ground is already comparatively dry, the heat used in evaporation is scanty and most of the absorbed heat energy is applied toward raising the temperature.

For this reason the temperature maximum is usually not in the south, but is displaced toward the southwest. This is also the reason why a directly western exposure is more than average warm. (In Fig. 101, the 0° line lies in the west-northwest the whole year.) The eastern exposure has more than average cold; only in the midsummer months does the value there exceed zero; in winter the nega-

tive areas on the chart extend into the southern exposures. Here is a fundamental difference between radiation and ground temperatures. According to Schubert's data, a 30° east slope receives more radiation than a west slope because the morning atmosphere is clearer. The ground temperatures, nevertheless, are lower in the east because of the shielding effect of moisture.

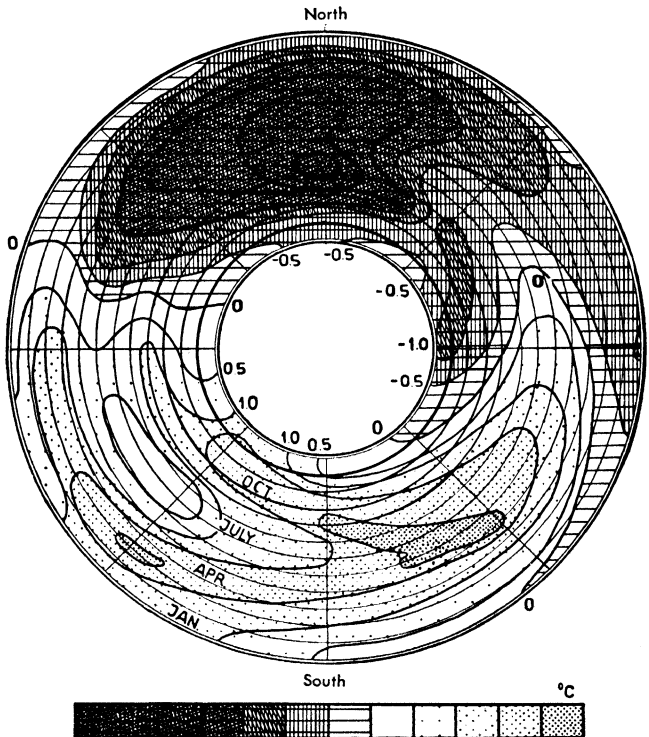

FIG. 101. Ground temperatures at a depth of 70 cm. in relation to direction of slope and time of year. (After measurements by A. Kerner near Innsbruck)

Proceeding from the normal location of the temperature maximum on a southwest slope, it would seem that the maximum in the southeast during the summer is abnormal. The cause, as E. Fritsch (425) and J. von Hann have shown, is the afternoon maximum of cloudiness during summer. It is precisely in the mountains, where these observations originated, that it is most usual for the afternoons

of even the fine days to be cloudy ("Fair weather cumuli"), frequently accompanied by thunderstorms and precipitation. This regular diminution of irradiation in the afternoon results in a displacement of the temperature maximum toward the southeast. It is a function of the macroclimate of Innsbruck and should not be expected throughout all Germany.

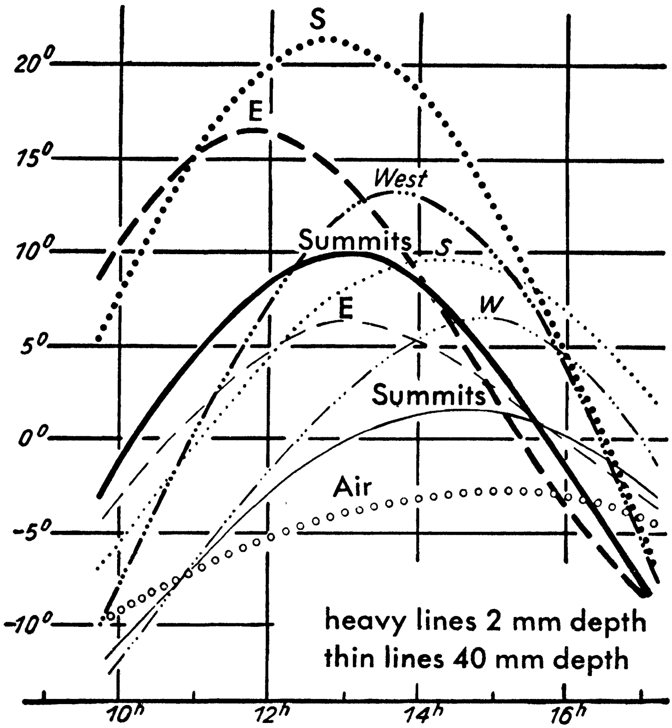

FIG. 101(a). Daily variation of ground temperatures in a sand dune of The Gobi Desert. (After W. Haude)

W. Haude (*426a*) has regularly made measurements of the temperatures of the ground in the dunes of the Gobi desert at the Edsengol stream (42°04′N, 101°17′E) about 1400 m) on the south slope, east slope, west slope and on the top of a big sand dune during winter 1931/32. Based on the publication of the original values by F. Albrecht (*423a*), I calculated (*5a*) the daily variation of temperature at the four observation places (Fig. 101a) for 12 undisturbed

days between December 18, 1931 and February 18, 1932. The average cloudiness of these days did not even reach one tenth. The course of temperature simultaneously recorded by a thermograph in a shelter on the sand dune is also given in Fig. 101a and indicates that in wintertime the air-temperature maximum is reached after 15h and is still 3°C below freezing point.

The temperatures of the ground are entirely different! The measurements at 2 mm depth, which correspond approximately to those of the surface, are drawn with heavy lines, those for 40 mm depth with fine lines; the same observation places are marked much alike. While the air is always below freezing temperature, the southern slope of the dune is heated up to nearly 22°C at noon; February 18, at noon, even 32.8° was reached. Here as well as on the top the temperature approximately paralleled the radiation. The maximum occurs at 13h. Eastern and western exposures show the expected shifting of the maximum toward forenoon and afternoon respectively. The greater heat of the surface on the eastern slope is noteworthy and is perhaps connected with the fact that towards east beyond the Edsengol stream an open gravel plain is located while towards west a region of dunes is spread.

The temperatures at 40 mm depth are parallel to those at the surface. Only they are shifted downwards and to the right corresponding to the decay and the lag of the descending heat wave.

Unfortunately, we do not have systematic series of ground temperatures for our climatic region, made with modern devices (see p. 125). In default of such series we want to mention an investigation made by a botanist.

From 1910 through 1917, A. Schade (*446*) took maximum and minimum thermometer readings in moss clumps on different slopes of the Elbsandsteingebirge. The instruments were inserted in the moss. The observed temperatures lie between those of the rock substratum and those of the air but far closer to the former than to the latter. The figures shed a clarifying light on the fundamentally different living conditions to which the plants growing close to the ground are subjected on various exposures.

A liverwort sod of Leptoscyphus Taylori covered a shady northeast-facing rock wall at Teufelsgrunde near Wehlen. At 50 m distance was a foliaceous moss clump of Webera nutans on a narrow south-facing shelf which formed part of a bell-shaped, rounded rocky summit exposed to the full strength of the sun. The maximum and minimum thermometers in the moss were read from time to

time. The table at hand gives, as an example of the observed data, the results for 1913.

TABLE 38

Period 1913	Temperature Maximum		Temperature Minimum	
	south-facing rock	NE slope	south-facing rock	NE slope
Nov. 15, 1912–Mar. 5	16.2	5.2	−7.7	−6.0
Mar. 5–Apr. 1	28.0	9.3	−1.6	−2.0
Apr. 2–May 2	47.1	13.0	−2.0	−2.2
May 3–June 2	55.1	16.0	2.9	1.8
June 3–July 6	55.7	16.4	7.0	6.9
July 7–Aug. 31	47.0	14.7	6.9	7.3
Sept. 1–Oct. 11	44.3	13.6	2.6	4.8
Oct. 12–Nov. 2	24.0	9.1	1.0	2.5
Nov. 3–Nov. 30	15.3	8.9	−2.6	0.0

The difference between the minima for the two exposures seldom exceeds 2°. But by day, when incoming radiation is effective the differences between the maxima are much greater. The average yearly maximum for the period from May 1912 through May 1917 in the case of the foliaceous moss on the rock with the southern exposure was 52.6°, while in the case of the liverwort on the northern slope it was only 15.9°C.

CHAPTER 22

Microclimatic Effect of Different Exposures to Sunshine

Before we discuss the temperature of ground air on slopes (Chapt. 23) we must mention certain natural phenomena in which the varied insolation on different slopes has a directly visible effect within a very limited space.

Ant hills in our climate and termite dwellings in the tropics exemplify tiny mountains on whose sides the most varied microclimates can be observed. We shall refer at present only to the exposures used by these animals in the care of their young. In Chapter 36, which is devoted to the relations of animals to the microclimate, this reference will be more fully developed.

The trunk of a tree standing in the open is circled by the sun in the course of a day. The bark receives a continuously changing radiation, which can be conceived as that falling on a vertical surface. Half the trunk at a time is under the influence of radiation; it is greatest on that portion of the bark turned toward the sun.

K. Krenn (*444*) has used the measurements of the total intensity of solar radiation at Vienna (202 m msl) and on the Kanzel summit in Kärnten (1474 m msl) in computing for several seasonally important days (cloudless weather being assumed) how much heat in calories is received by a standing tree trunk in the course of a day. The imaginary tree was considered as a circular cylinder with a diameter of 1 cm, and divided into 16 sectors, corresponding to the 16 main directions. For each sector the total heat was calculated from hour to hour and also summarized for the whole day. Fig. 102 shows, according to Krenn's beautiful method of representation, the relationships on the Kanzel top on Apr. 1st.

In the center of the sketch appears the tree in cross-section. The heat totals which build up hour after hour in the several sectors are plotted continuously outward from the bark along the radii and the corresponding hour points are connected. The spaces between the various hourly curves are black and white alternately for the sake of better visibility. The figures refer to hours of the day. The gradual working around of the sun from the eastern side of the tree to the western side is easily recognized. The outermost border line represents the amount of heat radiated to the part of the trunk in question, during the course of the day; what proportion belongs

to the various hours, can be read directly from the diagram. The boundary line is symmetrical with the north-south axis, since, in order to simplify calculations, the measured forenoon and afternoon values of radiation have been equalized.

This boundary line is repeated in Fig. 103 as a broken-line curve designated "Apr. 1," but on account of bilateral symmetry with

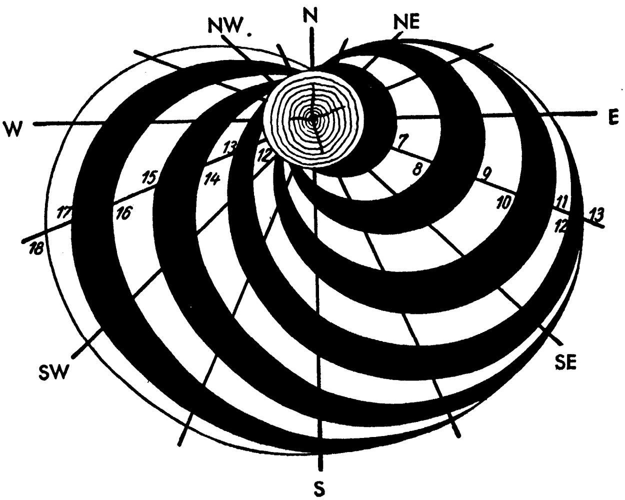

FIG. 102. Hourly progress of the warming of a standing tree trunk on a cloudless April first on the Kanzel summit. (Determination by K. Krenn)

respect to a N–S line, only the right half is drawn in Fig. 103. This illustration also contains for the Kanzel top the curve of July 1st as a characteristic of midsummer conditions and of Jan. 1st as characteristic of the winter. In the left half, the corresponding curves for the low-lying Vienna basin, where sunshine is much less frequent.

In the portion above the east-west line, the arrangement of the three curves is not surprising. In other words on the level as on the heights the northern part receives most radiation in midsummer because then the sun rises in the northeast and sets in the northwest. As winter comes on, the northern portions of the trunk are less favored. In general the mountain location (at the right) is more favored than that in the lowland (at the left). The January irradiation of the east and west sides of a tree on the Kanzel top are more than twice that similarly received at Vienna.

It is on the south side of the trunk that the most remarkable condi-

tions are found. Even on the plain the trunk receives more radiation in winter than in summer. The difference becomes very striking in the mountains. In spring (April) the part of the trunk facing directly south receives more than twice as much radiation as in midsummer and even this is exceeded on Jan. 1. No other portion of the trunk receives more radiation at any time. This is due to the low

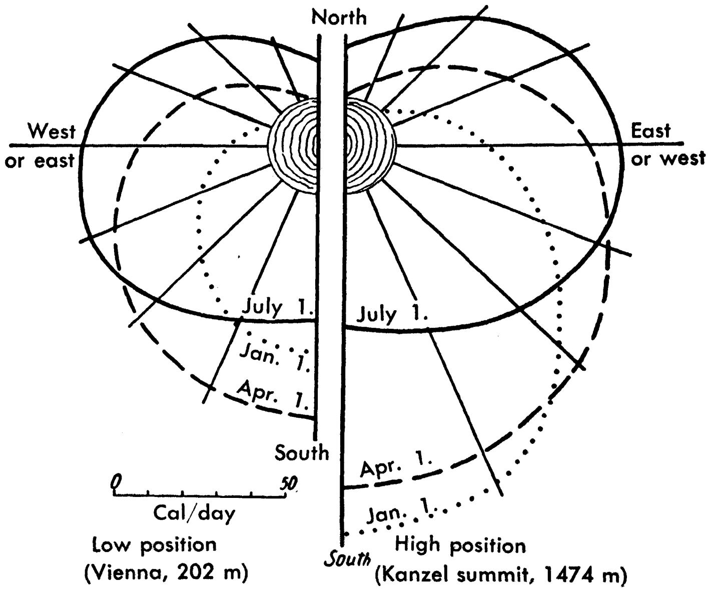

FIG. 103. Diurnal total of heat which a standing tree trunk receives on different portions of its surface on the plains and in the mountains. (After K. Krenn)

height of the sun at midday in the winter as has already been discussed in connection with fig. 100 (lower portion). (See page 220.)

The result of this is a great danger to the trees, particularly in early spring, when the nights are still very cold while the midday sun shines powerfully through the clear wintry atmosphere. The bark splits and loosens; it peels. M. Seeholzer (*448*), after the unusually cold winter of 1928–29, observed this phenomenon among red beeches at Spessart and has described it in detail.

Only some of the stronger trunks of a breast-high diameter exceeding 25 cm were affected, since only such have enough surface exposed to the sun. The body of the trunk and the bark were still frozen on account of the excessively low temperatures which held

over from winter into spring. In certain cases, where the beeches were standing at the southern edge of the wood, so much heat was received through radiation that the temperature in the bark rose above the dew point. "This condition," writes Seeholzer, "must have resulted in the bark's cracking and separating from the wood in blisters. Contributing to this effect was the fact that from January on, the beech has the highest water content of the year, and that the cell structure between bark and wood contains so much water when the sap starts that the bark easily separates from the wood. After a few hours, however, this part of the bark has again dropped below freezing and after sunset quickly followed the air temperature to a low point. The consequence was a very rapid and decided freezing with renewed water displacement and considerable shrinkage. The loosened bark returned to its original volume. But since the bark which was torn from its organic union with the wood could not be as closely knit again as before its separation, when the two were an organic unit, a weak bond resulted which could be broken by only a slight perpendicular pull of the bark." The same phenomenon of successive days strengthened the effect.

Fig. 104 shows such a bark wound on a 135 year old beech in the municipal forest of Lohr, which has already attained a length of 2.6 m. The bark is evidently bulged over a length of 1.4 m. The rent occurred in Feb. 1929; the picture was taken by Seeholzer in the following July.

E. Gerlach (*440*) observed the daily temperature range in the cambium layer on different sides of a tree. In 11 series of measurements on an old fir tree in the summer of 1926 he determined the following relation between time and place of occurrence of the daily temperature maximum:—

Hour of the day	2:30	3	3:30	4	4:30 P.M.
Place of the daily max.	SE	S	air	SW	N
Amount of the max.	31°	31°	24°	32°	24°

According to this, the various sides of the tree-trunk are related in amount and time of their maximum temperature values in the same way as are the different slopes on the sides of a circular hill. The shady north side receives its heat in the main only from the surrounding air — merely by conduction, not radiation; the temperature maximum there occurs even later than that of a southwesterly exposed tree trunk. E. Gerlach has also followed the penetration of heat from the bark into the interior of the tree by means of temperature measurements to a depth of 10 cm below the bark. It

does not differ essentially from the penetration of daily temperature fluctuations from the earth's surface into its interior.

In the case of logs lying on the ground, the insolation conditions are still different, but of no less significance in problems of forestry. K. Krenn (*444*) has calculated the figures for a log lying in a north

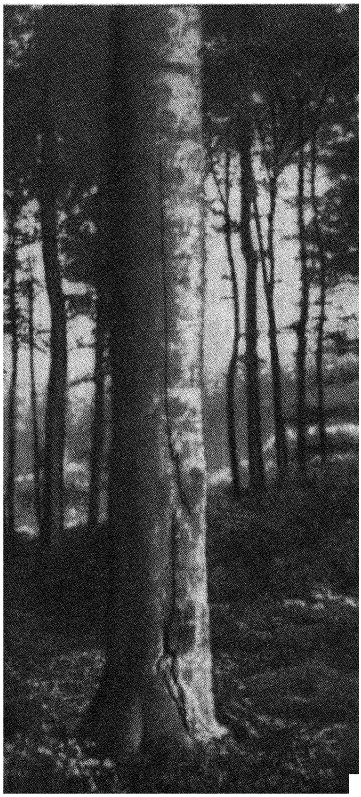

FIG. 104. Bark scale and cracks on the south side of a red beech as the result of the strong spring radiation with low air temperatures. (Photograph by M. Seeholzer)

and south line and also for one in a east and west direction. Fig. 105 shows an example of how the varied sunshine works out. It represents a cross-section of a tree trunk which lay in a NW–SE direction. On the southwesterly side there is a hot microclimate in and above the bark; on the opposite NE side it is shady and cool.

E. Schimitschek (706) has investigated the felling of such "captured trees" by the bark beetle (Ips typographus) and has shown that the development of the beetle around the trunk varies according to microclimatic conditions.

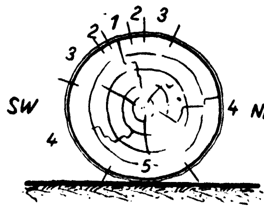

FIG. 105. Microclimatic zones on a fallen tree trunk. (After E. Schimitschek)

On segment 1, which is most exposed to the sun, the beetle has laid no eggs at all. The temperatures here reached 50° while the air temperature at a distance of 5 cm from the bark was not over 35°, and that at a distance of 1 m was only 30°. On the adjacent segments marked "2" eggs had probably been laid but had died. On segments "3" larvae had developed but later had dried up. It was only on that part of the log marked "4" (which is narrow on the sunny side but wide on the shady side) that the beetle developed normally. Yet on the underside of the log the death rate in the brood amounted to from 75 to 92% because in wet weather the log at and near the place of egg-laying was too damp for the beetle.

Now let us proceed a step further — from the trunk to the whole leaf-covered or needle-covered tree. The tree, as well as its trunk, is circled by the sun in the course of a day. The leaves on different sides of the tree consequently are subjected to quite varied radiation. Surveying the form of the tree, we can look at its upper surface as a slope which is not only exposed in every direction, but also possesses a varying slope, whose angle is a function of the distance from the ground. Observations of its microclimate are best made by observing its blossoms, for their development is the most sensitive indication of radiation and temperature relationships.

In May 1937, A. Scamoni (445) followed the blooming process of a 15 year old pine standing in the open at Eberswald. The tree, which had grown up standing free had developed 181 male blossoms on the four whorls which were studied. The following table shows the number which had bloomed in the several quadrants.: —

Up to the evening of	in the Quadrants			
	N	E	S	W
May 15	0	4	14	2
May 16	6	27	36	37
May 17	22	44	53	56

The greatest number of blooms was on the south and west sides, in agreement with temperature conditions. The first flowers to open were, however, on the south side, in accord with the radiation. Fig. 106 shows the blooming sequence for the fourth whorl of the tree,

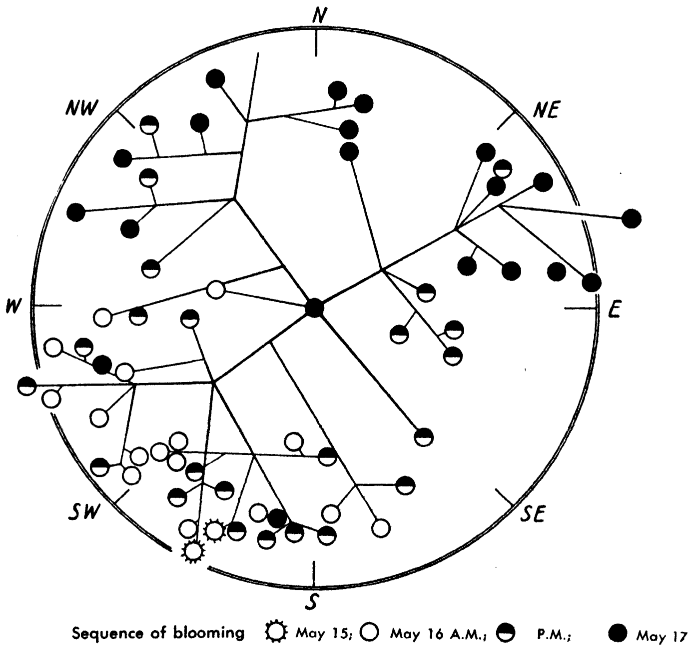

FIG. 106. Sequence of blooming of a 15 year old pine standing in the open at Eberswald in May 1937. (After A. Scamoni)

which was at a height of 1.1 m above the ground. The twigs, with the blossoms on them are diagrammatically represented as projected on the ground. Four stages of blooming are identified by suitable symbols, so that it is possible to get a picture of the entire process. In addition to the influence of exposure we have here the influence of shading by parts of the tree which extend farther out, the influ-

ence of the density of blossoms, of the flow of sap and of the individuality of each blossom. In this diagram, and even more so in nature there is a fertile field for microclimatic studies.

P. Filzer (*439*) has recently investigated the daily temperature march in the air surrounding a polygonum bush and dwarf pine growing in the botanical garden at Tübingen. O. Härtel (*441*) at Munich has described the blooming sequence in a circular tulip-bed with a sloping border, in connection with temperature and humidity measurements.

Our last example of the microclimatic result of varied exposure to the sun is the "compass plant." Very recently H. Schanderl (447) has given a comprehensive discussion of the whole problem from the microclimatic and botanical side. We shall follow his conclusions.

On southerly slopes it can be observed of the wild lettuce (Lactuca scariola) and several other plants in Germany, that they orient their vertically growing leaf-sprays in a north and south direction. The name "compass plant" was chosen under the assumption that directions could be deduced from the position of its leaves. The phenomenon has naturally nothing to do with the earth's magnetism but is a combined effect of direct shortwave solar radiation and long-wave heat counter-radiation from the earth. The ability to turn their leaves into one plane is a peculiarity inherent in certain plants and therefore only certain kinds are known as compass plants. But single plants are affected by their environment. Those growing in a moist habitat can easily regulate their heat by evaporation. In dry, stony habitats, however — especially on a sunny, southerly slope — they may lack the necessary supply of water from the soil and in such cases it is of advantage to orient their leaves so as to reduce their irradiation.

If such a compass plant is growing on a stony, steep, westerly slope or against a west wall, the counter-radiation of the wall (from the east) may be more unendurable than the direct radiation which at midday is greatest from the south. In this case the leaves take a position at right angles to the wall — east and west; botanists call it the "transverse compass position." Fig. 107 is a photograph of such a condition, taken by H. Schanderl. The wild lettuce which has grown beside a west wall has placed its leaves perpendicular to the wall. The name "compass plant" we can see is not quite suitable. For this reason H. Schanderl proposed the more accurate designation of "orienting plant," but since the older name has been established since 1850 he let the matter drop.

That both a north-and-south and an east-and-west arrangement can be present in the leaves of one and the same plant has been beautifully demonstrated by H. Schanderl through some specimens of this same Lactuca scariola. They were growing on a 30° westerly

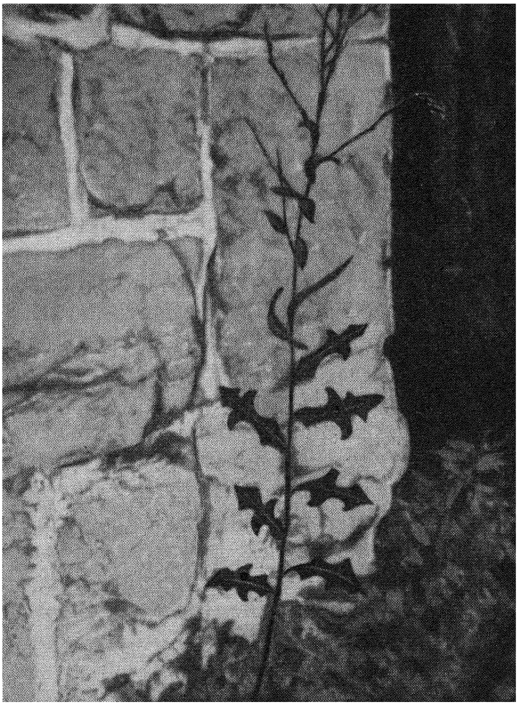

FIG. 107. Compass orientation of the leaves of a wild lettuce in front of a wall. (Photograph by H. Schanderl)

slope in the Würzburg province of Wellenkalk. Four plants close together had in all 627 leaves. On the sunny 10th of July 1931, Schanderl determined the compass position of each leaf. The result of his enumeration (the frequency distribution) he has presented as a percentage for each of the 16 main compass points. Fig. 108 shows this in graphic form with appended figures. A distinction was made between the leaves growing at a height of less than 50 cm. and those growing at a greater height from the ground. The black part of Fig. 108 applies to the former; the part enclosed by the broken line, and the figures in parentheses, belong to the latter.

A glance at Fig. 108 immediately shows that the lettuce leaves in the lower half meter stand predominantly east and west, while the higher growing leaves are prevailingly north and south. The latter are protecting themselves mainly from the direct radiation of the

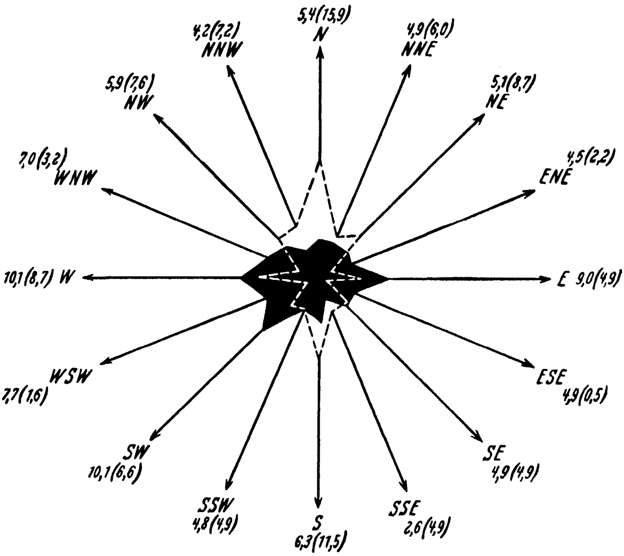

FIG. 108. Leaf orientation of the leaves near the ground (black) and the upper leaves (broken line) of the lettuce on a westerly slope. (After H. Schanderl)

sun; the former, more against the counter radiation of the west slope. This indicates, as Schanderl has proved by further experiments, that the leaf position depends on the radiation climate of the particular location where the plant is growing.

A special variety of compass plants is that which Br. Huber (*442*) has called the "gnomon plant." Aster linosyris, the "golden mane" aster, has narrow lanceolate leaves which normally lie horizontally. In dry habitats, exposed to strong radiation, they assume a vertical position. On steep southwestern slopes, however, the leaves on the side next to the slope are combed forward uniformly toward the south and at the same time stand quite exactly in the direction of the maximum midday height of the sun.[1] At the time of strongest

[1] The ancient gnomon had a vertical pin. It was the predecessor of the sun-dial, whose pin should be parallel to the earth's axis. The word "gnomon" is used here in the general sense of "sun-pointer" since a plant in "gnomon setting" points to the sun.

radiation the plant presents the least possible surface to the sun. In contrast to the compass plant, the gnomon plant, even on a western slope, takes the same position with reference to the south, deviating, at the most, not more than 10° from the direction of the midday sun. There is no doubt that the phenomenon exists, as H. Schanderl has demonstrated repeatedly; its explanation is still uncertain.

In these last remarks we have wandered far into the field of botany. Now we shall return to the ground temperatures on the various slopes, and in the following chapter shall investigate the relationship of slope to the air near the ground.

CHAPTER 23

The Skin of Air on Mountain Slopes

Although sloping ground favors the sliding down of cold air and the rise of warm air, we find, even on the slopes, a layer of air near the ground which has the peculiar properties described in the first part of this book. Like a skin of air it clothes even steep cliffs and determines the climatic habitat of the plants growing thereon.

We have a systematic investigation of the properties of this air film which R. Geiger (*454*) carried out in 1926 at the Forestry Meteorological Institute of Munich. It was directed by A. Schmauss under the sponsorship of Th. Künkele (*461*). The experimental area was the Hohenkarpfen, an isolated mountain cone on the border of the Württemberg Alps.

There were 34 observation stations located on slopes of different directions and at different heights. The sketch map (Fig. 109) shows by the configuration of the contours how regular the cone is on all sides. Beside station *A* on the summit, there was a circle of 8 stations (marked *W*) on the uppermost slope, which lies at an average inclination of 30°. On the shoulder of the cone, where the steep cone of the white Jura passes into the gentler 11° slope of the brown Jura there were 16 stations (marked *H*), while still further down and outside the limits of Fig. 109, there was another circle of 8 stations. At all points maximum and minimum temperature readings were taken at a height of 25 cm, while at 8 *H* stations and on the summit, measurements were made at 1 m height also. The thermometers were mounted at places where the slope was quite perpendicular to the desired compass direction and where there was no disturbing bush or tree in close proximity.

Most of the mountain was in sheep pasture; only on the east and west slope was there shrubbery with occasional trees, as shown in Fig. 109. The south slope was the only one entirely free from vegetation.

Fig. 110 shows a lateral section of the mountainside; the vertical scale of the profile is doubled. In order to be able to show temperature relationships in the air layer near the ground its height had to be magnified 50 times. In the upper part of the diagram the daily maxima are represented; in the lower part, the minima, based on the summer observations of 1926—all directions of slope being aver-

aged together. The course of the isotherms, which follow the contour of the ground, shows that a ground air layer with pronounced temperature stratification, is to be found on even the steepest slope. Within this layer a temperature decrease with increased height prevails by day even as it does over flat ground, while by night the

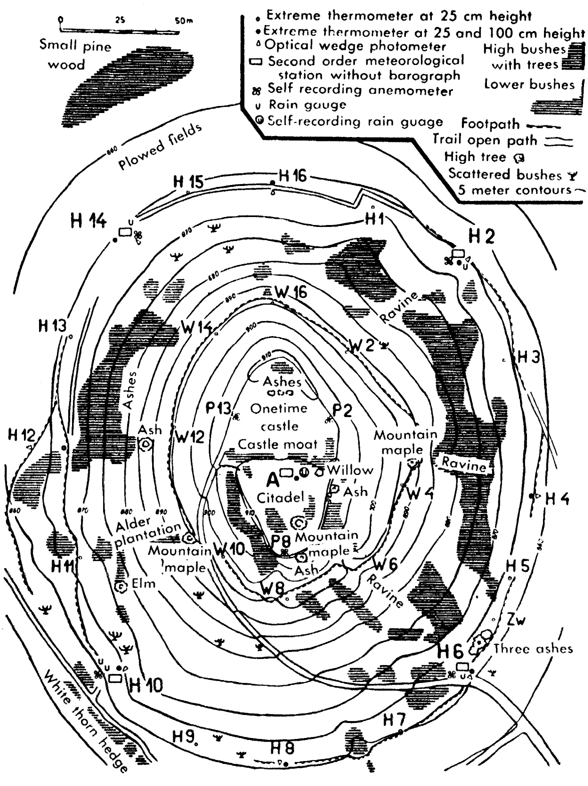

FIG. 109. Arrangement of observing stations for a climate-measuring demonstration at Hohenkarpfen in the Swabian Alps. (After R. Geiger)

opposite is true. The temperature distribution at night on a valley wall, which is represented at the lower right in Fig. 91 is what we find to a lesser degree in the air skin on the Hohenkarpfen. By day the distribution corresponds perfectly, with cold and warm air interchanged; the valley and the upper plateau are now warm while a "*cold* storage" lies in front of the slope.

The data from all directions of slope, which were all summarized in Fig. 110, prove the existence of the air skin. We are next interested in the influence of slope direction on the temperature relationships within this skin layer.

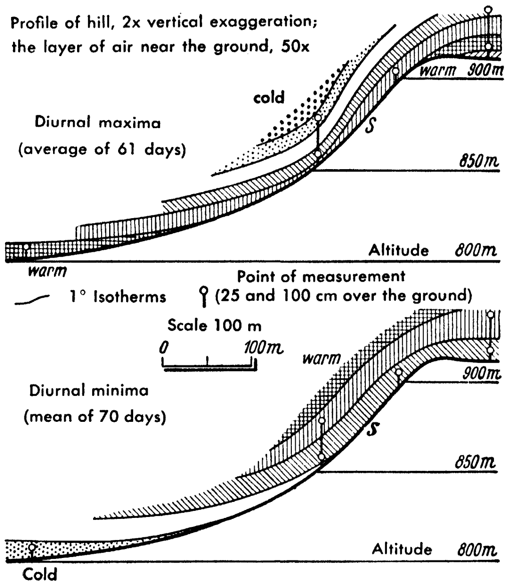

FIG. 110. Formation of air film by day (above) and night (below) on the slopes of the Hohenkarpfen

It is best to start from our earlier remarks on direction of slope and ground temperatures. The air temperatures near the ground will vary approximately as the ground temperatures. Hence the air will be coolest in the northern slope and the hottest daytime temperatures are to be expected on a slope between the south and southwest. This is confirmed by Fig. 111. But beyond that we must remember that winds and convection are easily able to remove the air which is heated or cooled at the surface, because slopes are particularly exposed to wind and the inclination of the ground favors convection movements.

For this reason vegetation plays an important role in the microclimate of sloping ground. Where plant growth restricts convection, the locally controlled slope climate is better developed, but where a slope is entirely free from vegetation, the differences disappear.

Fig. 111 will serve to prove this. It shows the distribution of temperature maxima on the Hohenkarpfen on the average for 70 summer days. The upper circle represents diagrammatically the measurements at a height of 25 cm above the ground. Small circles indicate the positions of the various observation points, easily located

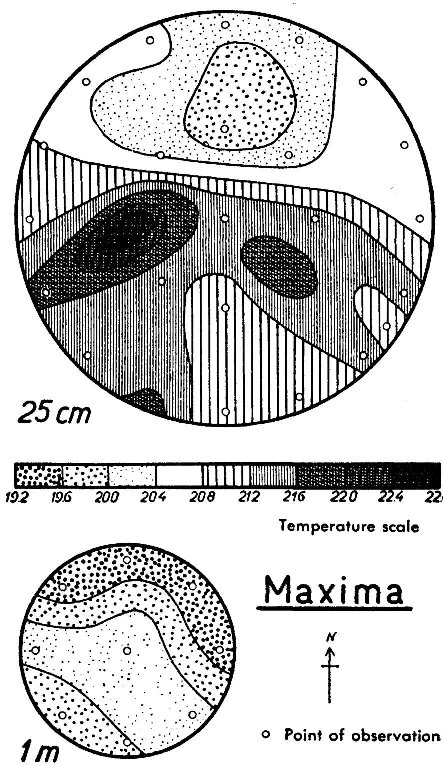

FIG. 111. Distribution of the highest temperatures of the day in the air film at Hohenkarpfen

on the map in Fig. 109. The circle at the lower left in Fig. 111 contains the temperature distribution at a height of 1 m according to the observations on the summit (*A*) and at the *H* stations. In comparing the observations at the two heights we are to imagine the smaller, lower circle as expanded to the dimensions of the larger one.

That the air skin is universal, appears from the generally lower temperature at the 1 m height (dotted surfaces only!), as compared

with that at 25 cm. Here at 25 cm the ground temperature makes itself felt — the more so, the steeper the slope. As the inclination increases, so does the influence of stronger insolation as compared with the greater possibility of equalizing movement outward from the slope. In Fig. 111 we may deduce this from the fact that near the *W* stations the isotherms are crowded more closely than near the *H* stations. On the steepest part of the slope the different directions of slope vary the most. The observations on the lower, flatter part of the slope, which are not reproduced here, do not show any directional effect to speak of. There the temperature of the air near the ground is entirely dependent on such surface conditions as grass, tillage, etc.

It was to be expected that the lowest temperatures would be found on the north slope. It is surprising, however, that the maximum on the southerly slope is divided in two — one in the southeast and a stronger one in the southwest. Here it is the influence of the lack of vegetation on the south slope which modifies the extremes of a purely southern climate. A proof that this is really the case is afforded by the measurements at the intermediate station *Zw* (Fig. 109). This *Zw* station was inserted between *H5* and *H6* where a bare channel ran down the mountain from W4. If the unhindered air movement on the south slope were really the reason for the mitigating of the midday temperature, a similar phenomenon must necessarily present itself at the *Zw* station, where the up-slope wind must be guided into the gap between the thickets and so over *Zw*, while the two neighboring stations *H5* and *H6* lay in front of the bushes which hindered the air flow. Fig. 111 shows that the two stations *H5* and *H6* had a higher average midday temperature than the intermediate *Zw* station, thus confirming the theory. The uniform distribution of night temperatures, which are not indicated here, gives assurance that the daytime measurements referred to are not fortuitous nor the result of errors in the method of measurement.

Systematic measurements of atmospheric humidity as found in the air skin on slopes in different directions are unfortunately lacking. They would be very helpful in many practical questions, such as the furtherance of forestry in dry climates. O. Härtel (441), in his measurements to which we have referred, made in a circular, slightly mounded tulip bed of 1 m diameter, found that on the southern slope the noontime humidity 2 cm above the ground was 10% lower than on the northern slope. It is evident that considerable differences are to be expected.

A word should be said here about the distribution of precipitation around a hill.

From macroclimatology we are familiar with the fact that in middle Europe the prevailing west winds result in the west side of the mountains receiving the most precipitation. The air has to rise up the side of the mountain; its pressure falls; it cools and approaches the dewpoint. If this point is passed, clouds and precipitation follow. The cooling with ascent amounts to 1° per 100 m vertical rise. On the small scale with which we have to do in considering hills and rolling country — particularly in microclimatology — such thermodynamic considerations are obviously out of place. The distribution of precipitation is determined rather by two other factors — winds and ground slope.

Measurements which R. Geiger (*454*) initiated on the Hohenkarpfen led to the following results: — If the precipitation be measured with rain gauges whose mouths are mounted horizontally, as is customary, the slope toward the wind receives less precipitation than the slope away from the wind. On the windward side the precipitation is carried away by the wind which strikes the slope and attempts to flow around and over it. On the lee side, however, a quiet area with irregular, weak air-movement forms in the wind "shadow." Here is where the precipitation falls, which was whipped over the hill. On a hill, therefore, the distribution of precipitation is exactly the reverse of that on a high mountain; the east side receives more, the west side less, if the observation is made with a normally placed rain-gauge. This microclimatic rule applies to easily drifted snow to an even greater extent than to rain.

Everyone has noticed that the snow lies especially deep behind fences, boulders and ridges of ground. As a general rule, which works out practically in forestry and agriculture also, the microclimatic phenomenon just described is given too little consideration. The often made statement that the west side of a forest is favored with precipitation in comparison with the east side is based on a confusion between macroclimatic and microclimatic experience and at least in this general form is unjustified.

In the distribution of precipitation around a hill, the influence of ground slope is to be added to that of the wind. What is always of most interest to the practical man is the precipitation falling on the actual inclined slope, not that which falls on the artificially located horizontal mouth of the rain-gauge which, moreover, is a meter above the ground.

Comparative measurements of a horizontal rain-gauge and one

whose mouth was parallel to the ground surface on the Hohenkarpfen showed that the 20° slope on the side of the hill turned toward the wind received more precipitation than the level ground. The excess resulted from the wind velocity prevailing during the rainfall. This excess was as follows:—

At wind-speeds below 4 m per sec	3%
At wind-speeds of 4 to 5 m per sec	11%
At wind-speeds of over 5 m per sec	27%
In a single case (thundershower)	34%

The brisker the wind, the more obliquely the rain beats down and the more this favors the sloping ground. On the side of the hill which is sheltered from the wind, however, where the rain falls straight down, 5% less was measured on the slope than in the horizontal gauge.

It is recognized that the just-mentioned effect of ground slope opposes the wind effect and partially annuls it. The two factors must be weighed one against the other.

CHAPTER 24

More on the Influence of Topography

In Chapter 19 we studied temperature relationships by *night* in valleys and on hillsides. The effect of land form on the microclimate by *day* was presented in the three preceding chapters, so that we can now describe the temperature relationships throughout the whole day. To this we now add a consideration of the other meteorological elements insofar as they are of microclimatic interest and observations are available.

To represent the daily temperature march on slopes, in valleys and on mountains we can again make use of a series of experiments which, at the instigation of Th. Künkele (*460*), were carried out in 1931 and 1932 by R. Geiger, M. Woelfle and L. Ph. Seip (*455*) of the Forestry Meteorology Institute at Munich. The site of the experiment was the Gross Arber in the Bavarian Forest. A meteorologi-

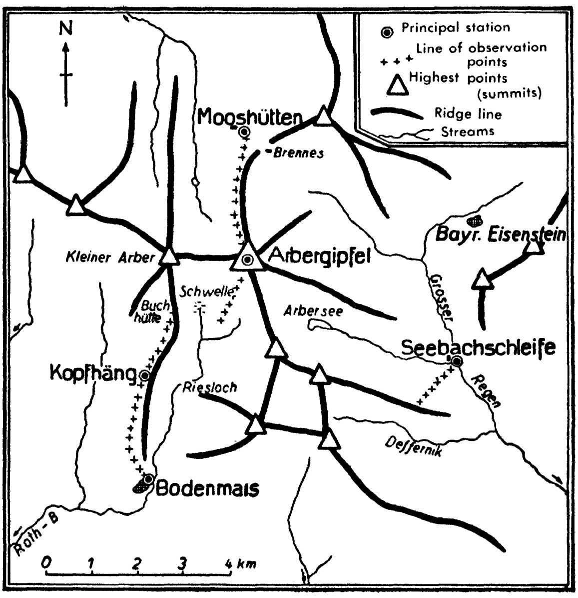

Fig. 112. Survey of the experimental arrangement at Arber

cal station (standard arrangement in German shelter) was erected on its summit at 1447 m above sea level. Two valley stations of a similar sort were located at Bodenmais in the southwest (665 m) and at the Seebach slide in the east (645 m). Besides these, there were two intermediate stations — Kopfhäng at 1008 m and Mooshütten at 946 m. Between these main stations, there were located 99 measuring points for the determination of night temperature, along the lines of crosses shown in Fig. 112. The data from the line of stations, which extends from the Seebach slide up the slope toward the southwest have already been presented.

Fig. 113 shows the daily course of the temperature at three main stations as an average of 25 clear days in the months of May and June. The critical reader may complain that the curve does not repeat, i. e. that the temperature at 24 hrs. is not the same as at 0 hrs. The choice of days is to blame. Clear weather in spring brings a rise in the temperature level; therefore after 24 hrs. it is generally warmer. This is also true for the humidity curve in Fig. 114. After a clear day the atmosphere is regularly drier.

A glance at Fig. 113 confirms the old fundamental rule, propounded by A. Woeikof, that convex areas have a moderate climate while concave areas have an extreme one. A valley shows a large daily fluctuation of the air temperature as compared with a mountain peak. R. Reidat (465) was able to verify this law in a microclimatic study of the region around Erfurt. The difference between maximum and minimum temperatures in the city of Erfurt (221 m msl), and on the Inselberg (914 m msl) which is 40 km away, were:

For the month of	Jan.	Mar.	May	Jul.	Sept.	Nov.
In Erfurt	3.6	6.8	9.7	9.6	8.1	3.3
On the Inselberg	1.4	3.1	5.4	5.0	4.0	1.4

That this difference is far greater than the normal decrease of daily temperature range with altitude, indicates, therefore, the effect of the topography.

According to Fig. 113 there exists a decrease of temperature with height from 8 A.M. to 6 P.M., while from 10 P.M. to 6 A.M. there is a nocturnal temperature inversion. The highest nighttime temperature (15.6°) is on the slope; next comes the valley (14.9°); finally at a considerable distance, the mountain peak (12.2°). The abrupt transition between day and night is evident in the curve of the valley temperature. When the sun is first able to shine into the valley in the morning a strong temperature rise begins. Direct heating by the sun is reinforced by heat from the neighboring slopes.

The narrowness of the valley moreover is at first a hindrance to air movement which would favor cooling. When, toward evening, the sun has disappeared behind the mountain, there follows an abrupt fall in temperature.

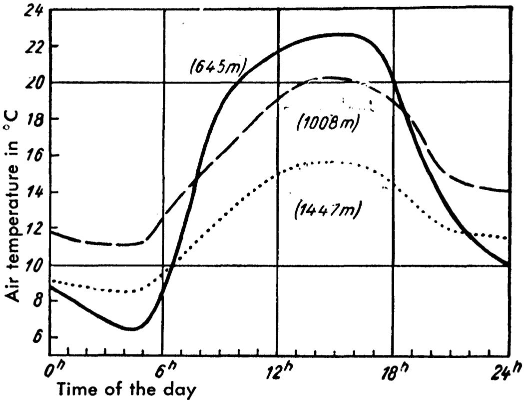

FIG. 113. Daily course of temperature on clear spring days at different heights at Arber

Quite different is the daily range on the summit and, indeed, on the slope. In the temperature curve of the slope stations we notice the continuous uniform rise between 6 A.M. and noon. However great may be the influx of heat on the moderately inclined south

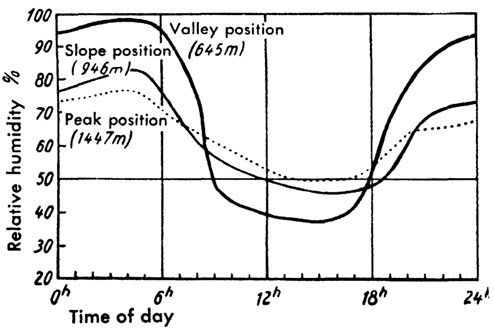

FIG. 114. Daily course of relative humidity on clear spring days at different heights at Arber

slope where the station is located, the rate of temperature rise cannot exceed a definite figure. Otherwise the up-slope wind is so strengthened that it causes a compensatory ventilation with a resulting temperature drop.

Similar relationships to those on the Arber have since been demonstrated by A. Lauscher-Wittmann (462) on the eastern slope of the Wienerwald mountains, by N. N. Trankevitch (470) as probe measurements on an experimental area of the trans-Baikal research station, and at other places.

Fig. 115 shows the decrease of temperature with height in relation to weather and time of day, for the stations on the Arber — the upper part, the coldest. Air masses are chosen as the most reliable

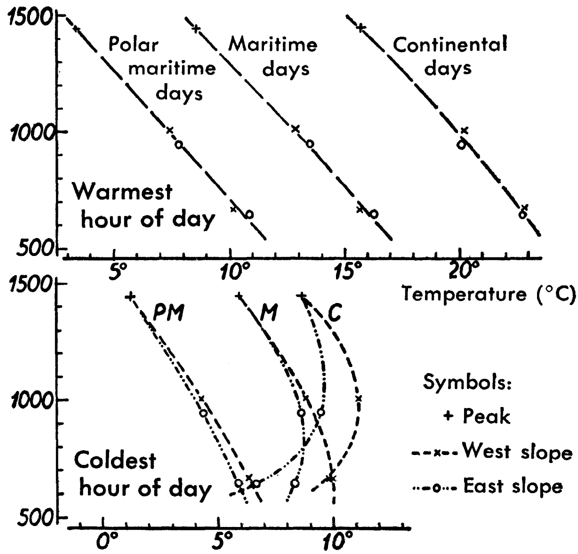

FIG. 115. Temperature variation with altitude by day and night at Arber in relationship to air mass

indicators of general weather conditions. Days with polar maritime air influx (*mP* days) are days with cold waves and gusty, showery weather. These are the days with lowest temperatures. Consequently the corresponding curves are those farthest to the left in Fig. 115. On days with maritime air (*m*), rainy, windy, "west weather" prevails. The days with continental air (*c*) are the quiet, sunny fair weather days of spring — hot all through the daylight hours but cold at night.

It so happens that by day the weather has little to do with the temperature gradient; it remains constantly between 0.87 and 0.96°

per 100 m, never quite reaching the adiabatic gradient of 1° per 100 m. Wilh. Schmidt (*466*) found only a few days when the gradient on the slopes of the Gumpoldskirchen at Vienna exceeded the adiabatic. In the extensive investigation of F. Innerebner (*457*) on the valley slopes north and south of Innsbruck, superadiabatic temperature gradients were found only as the consequence of local overheating (city influence) — never under normal conditions on the open slope.

In this there is a difference between the free atmosphere and that found on hillsides. In the former, much greater gradients than 1° per 100 m are found about noon on hot days as aerological measurements in many places have proved. But on slopes along which the heated air slides easily upward, adiabatic gradients are rarely exceeded.

The nocturnal temperature inversion has already been described in general. How its form depends on the weather may be seen from the lower portion of Fig. 115. It is weakly developed on *mP* days but very marked with continental air. A distinction must be drawn here between the west and east slopes of the Arber. The temperature inversion on the east slope is always more pronounced than on the west. This is not to be considered as a directional effect; it is rather a result of the microclimatic conditions at the stations. The west stations are in this case more openly situated and consequently more exposed to the wind; the east stations, on account of their being shielded from the wind, are truer to their local climate. The arrangement of the three selected groups of days, according to temperature, from *mPk* to *cPw* applies by day throughout, but by night only to the higher parts of the mountains. As can be clearly observed in Fig. 115, radiation and cold air movement can make it as cold in the valley in spring as it becomes through the advection of polar maritime air masses. This figure depicts, therefore, the two possible occasions of damaging spring frosts — radiation frost and advection frost.

Three stations with macroclimatic observational methods, placed at 800 m altitude steps on the east and west slope of Arber, furnished the bases of Figs. 113–15. The question now arises, whether a linear interpolation of temperature and humidity values is permissible in order to find the climatic conditions at any point on the slope between these stations.

As an answer to this question, Fig. 116 shows the mean minimum night temperature for all Arber stations on the spring nights of 1931 and 1932. All the nights have been used in the right half of the

figure; only the clear nights in the left half. The following conclusions may be drawn.

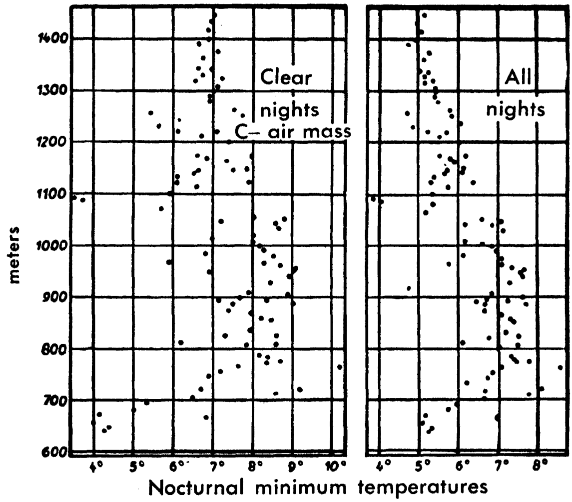

FIG. 116. The scattering of night temperature at different altitudes at Arber

1. The scattering of nocturnal temperatures is extraordinarily great. The influence of the microclimatic condition often far outweighs the influence of altitude. For instance, places at 700 m msl may be 3° warmer, and also 3° colder, than the peak at 1400 m.

2. The extent of scattering decreases with altitude. If we determine the average temperature of single altitude steps and calculate, for the stations within them, the average temperature difference corresponding to the average altitude of each step, we find: —

for the step from	650–850	850–1050	1050–1250	1250–1450 m
on clear nights .	1.1	0.6	0.8	0.3°C
on all nights . . .	0.6	0.4	0.4	0.2°C

so that in general there is a decrease of scattering with increase of wind velocity with height, since stronger winds disperse local influences.

3. A comparison of the right and left sides of the figures teaches that microclimatic peculiarities are fixed — microclimates being locally conditioned. Measuring points which have low night temperatures, have them consistently. (For example, consider the two very cold stations just below the 1100 m altitude).

We shall come back to these questions in Chapter 40 in considering damaging frosts.

As we can pass from the laws of slope climates shown in Figs. 113–115 into more restricted cases, so also can we turn our attention outward where topographical influences have still greater scope.

In his Zugspitze experiments, A. Büdel (*450*), with the help of the temperature and humidity records on the cable-car line from Obermoos (1234 m) to the Wetterstein crest (2805 m), determined the climatic relationships on the west slope of the mighty Zugspitze massif. His publications in 1929–1931 give us an excellent insight into what he calls "Mountain atmosphere," "By 'mountain atmosphere'," he says, "we must not imagine any homogeneous air layer resting on the slope. Rather, there are various bodies of air lying over one another and beside one another, whose existence depends on the form and condition of the ground, on the exposure, the relationships of incoming and outgoing radiation, on air currents, etc. The centimeters of microclimatology are, perhaps, 'meters' in the consideration of mountain atmosphere, where quite different energy quanta are concerned." If we consider that in Büdel's experiments the cabin of the cable car on whose roof the recording apparatus was mounted was as much as 130 m above the ground, we can imagine the grand scale of the investigation.

The combined effects of the various mountain atmospheres constitute the mountain-range atmosphere. And this, on its part, extends an influence on the air masses far beyond the limits of the mountain system. We have only to think how the foehn effect reaches far into the lowlands. A. Büdel calls this the "Zone of influence of the mountain range." Investigation of topographic influences of such great extent is, however, entirely a problem for macroclimatology.

The difference between mountain and valley produces its own wind system by day, as well as by night. In place of the nocturnal down-slope wind (see p. 212), an up-slope wind appears by day; it is stronger in proportion to incoming radiation and to the steepness and bareness of the slope. Anyone wandering in the mountains can easily observe it by aid of the smoke from mountain huts or in the "air skin" by the fluttering of winged plant seeds. Its vertical depth increases with distance up the slope, just as, correspondingly, the down-slope wind increases in depth as it flows downward.

In place of the nocturnal down-valley wind there is during the day an up-valley wind, which used to be known merely as a valley wind. Fig. 117 gives the plan of interaction of the up-slope wind and

the up-valley wind according to A. Wagner (*420*). This diagram can be easily understood by comparison with Fig. 97 and needs no further comment. A. Schmauss occasionally verified the circulation scheme by means of direct observations of smoke- and haze-layers (*465a*). The up-valley wind can reach greater speed than the down slope wind and always has a refreshing effect upon the bio-climate of the valleys. This was verified by A. Jelinek (*457a*) by his measurements of the cooling power in the valley of Innsbruck.

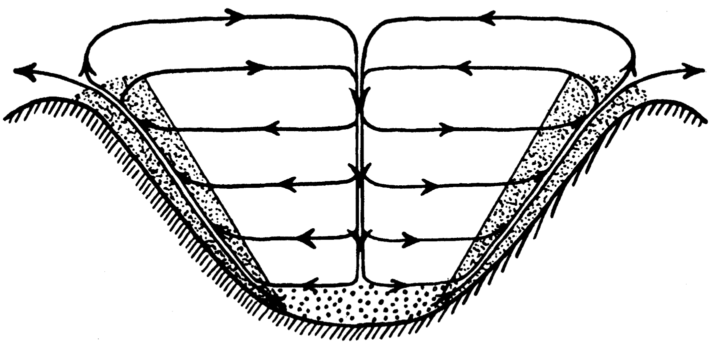

FIG. 117. A. Wagner's diagram of the air circulation in valleys by day

The up-valley wind occurs with great regularity at many places. Thus, H. Kinzl and A. Wagner (*459*) report from the Peruvian Andes that in the Santa valley the eucalyptus trees are decidedly out of shape as a result of the valley wind, and that the native population make use of it in the afternoon for winnowing the threshed grain.

Plant cover is an excellent indicator of slope climate. In describing the "warm slope zone," examples of this have already been given, but only with reference to the effect of nocturnal temperatures. The diurnal effect, resulting from variations of sunshine, the concurrent drying effect and differential ventilation, is not less important. Geographical literature is full of such cases. We shall mention only a few by way of illustration.

Of the Buntsandstein area in the Pfälzer Forest, Th. Künkele (*461*), from a forester's viewpoint, writes as follows: "Whoever stands on a mountain top and looks out over this range, apparently a geologic unit but with decided local characteristics, dissected as it is by narrow valleys with precipitous mountain walls, sees at first glance toward the NNE (on the slopes most exposed to sun and

wind) an almost perfect, dark blue sea of pines with hardly a deciduous tree in sight. But if he turns his gaze toward the SSW it is amazing, even for the forester, to observe how completely different is the appearance of the forest, for this side is covered by a soft green, shimmering expanse of deciduous trees with only a slight intermixture of evergreens. This naturally appears on maps of forest layouts and hiking clubs, where the green and yellow colors designating deciduous woods in contrast to other tones for evergreens represent the varied orography of the mountain. An assessment schedule would give a similar picture, since opposite sides of the same peak (with the same geological strata) often differ in value, sometimes by 100%.

K. Sonntag (*469*) in his description of the climate of the Kalmit (Rhine Palatinate) clearly portrays the nature of slope climates. "In the make-up of the forest cover, windward and lee sides oppose one another and the relative exposure to insolation is also important. On the west, southwest and south, the trees are scrubby and crooked, with stunted crowns. Oaks and beeches grow mostly in bush form; one ground fir is found. On the north and east, trees of similar age grow much higher, quite upright in the east. The southeast slope is equally favored by radiation and wind; it receives less wind and not too much sun; consequently it does not become too dry, neither does it get too cold. Stately beeches, firs, oaks and the finest pines are found there."

H. Huttenlocher (*456*) working from a geographer's viewpoint, in 1923 studied the influence of exposure on the plant world, the forest, utilization of the slopes and civilization with special reference to his Würtemberger home.

F. von Kerner (*458*) gives a truly masterful microclimatic exposition of the occurrence of the Alpine rose in the Gschnitz valley south of Innsbruck. His description (slightly abbreviated) follows:

The Alpine rose, which flourishes on silicious soil, and whose leaves are rusty on their under side, finds its lower limit of occurrence at an altitude of about 1550 m on the south flank of the outermost Gschnitz valley. In the inner parts of the valley close to the glacier it occurs as low as 1320 m. It is also found locally at the foot of the inner side of the south branch of the old glacial moraine, which extends into the outer valley, also at a place on the outer side of the north branch of this moraine — in both these places it occurs at less than 1200 m.

In the latter location several conditions unite to set it back thermally in relation to its surroundings. First there is the northeasterly outlook in the midst of country having an otherwise southerly exposure; then

the full force of the cold northeast and east winds, from which the south flank of the moraine wall is protected; on the other hand the location in the shadow of the foehn, to which the neighboring south slope is fully exposed, and finally — of less significance — the cold mountain wind sweeping over, which comes out of a gully that continues into the notch between the moraine wall and the northerly valley slope, accompanied by a brook which follows the same course as this stream of air. When the brook is frozen, this proximity may have a cooling effect. Both flanks are stone walls some 20 m high, and on the north flank is where the Alpine rose grows, in a situation of local contrasts. The mild south slope, is mostly covered with fir and larch needles — of brownish tone; the steeper north slope, thickly overgrown with moss — is clad in shimmering green.

When a snowfall occurs in summer or early autumn, the white covering lingers longer on the habitat of the Alpine rose than elsewhere on the northern side of the valley. In spring the locality is said to hold the snow three weeks later than its surroundings. Sleds are still used on the nearby roadway — according to reports — after all the other roads in the neighborhood are open.

Summer temperature measurements of the upper ground layer at midday showed a lag of 3 to 4° of the mossy moraine wall slope as compared with the dry slope. Measurements of the relative humidity in the foehn gave values of 32 to 36% on the flank wall openly exposed to its impact, as contrasted with 54 to 62% on the side protected from the wind. Numerous Piche evaporation measurements at one place where the foehn blows and another place protected from its force, showed that at the latter place the amount of water evaporated was, on the average, 39% of that evaporated at the former. The least and greatest ratios were 28% and 46%. The meadow separating the cool, moist, mossy slope from the above mentioned brook, is called "Vernail," an old flower name with a certain significance. "Vernail" comes from "vernalis." This may be thought of as a reference to the locality being still spring-like after all the surroundings have passed into summer, or in the sense that spring flowers bloom in the meadow while snow and ice are still in the neighborhood.

It seems harder to explain in terms of local climate, the occurrence of the Alpine rose at the foot of the inner side of the southern moraine wall, which is turned toward the Gschnitz valley floor — i.e. at the foot of the south side of the valley, more than 300 m below its normally lowest limit of occurrence on this side. It may be that the ground moisture, here near the valley water table, is greater than higher up on the slope. The ground formation may have a decided thermal effect. The valley floor, surrounded by U-shaped moraine walls, is the site of the development of strong winter inversions. They were discovered many years ago at the place where the Gschnitz brook now breaks through the stone wall of the moraine, that is, at the outlet of the

winter cold lake. In 15 cases out of 55 (from mid-January to the end of March) the nocturnal minimum temperature at this point was more than 3° lower than at a place 50 m higher on the left-hand valley slope; in seven cases this difference was more than 5°, and in one case it was more than 7°.

CHAPTER 25

Concerning the Range of Validity of Meteorological Stations

In the network of meteorological observation stations which nowadays covers every civilized country, the disturbing influence of the air layer near the ground is avoided with comparative ease by locating the instruments at least 2 m above the ground. It is more difficult in considering the microclimatic influences of topography, plant cover and population to find a station which corresponds to the average relationships between its nearby and more distant surroundings — which is, as we say, "representative."

The chief requirement of a representative station is that it shall have a wide range of validity. This is the ideal of macroclimatologists. The variations of topography make the proper choice of such a station difficult. It is therefore necessary to take up here the question of the range of validity of a station where macro- and microclimatology are most closely related.

The better the influence of topography on climate became recognized and the greater the demand for accuracy and utility in meteorological observations, the louder also became the cry for a denser network of stations. This desire originated in mountainous country. But the farther climatology progressed, the more limited became the range of validity of stations on the plains. As early as 1911, K. Knoch (*484*) showed how important, even on the plains of northern Germany, were slight variations in topography. And in view of the increasing number of legal decisions and the services required by agriculture, commerce, business and industry, attempts were made for every place in question to have a meteorological station close at hand. M. Topolansky (*500*) said, "There can never be enough stations."

There are, however, decided difficulties in the way of such a wish. A. A. Hettner (*481*) once demanded the expansion of the station network in the name of geographers, K. Knoch (*485*) pointed out in the name of meteorologists that it would require a lot of money. And even if the money were available the observers must first be found. With the severe requirements made of each observer as to faithfulness, carefulness, and tenacity, whereof the user of the observations has for the most part no conception, this is a difficult task. But even if personnel and money are available, still new installations

are justifiable only if the data obtained can receive the essential amount of attention and consideration. This too requires much means and strength.

We must therefore face the fact that there are practical limits to the density of a station network. There is, however, another remedy. Instead of setting up new stations, we can try, as our knowledge increases, to extend the range of validity of those we have. To this end the words "range of validity" must first of all be given proper interpretation.

Originally this meant that the numerical data of the observation stations could be considered applicable to a wider territory. The range of validity of a station ends where the numerical departures from the station become too great to be neglected on the basis of the accuracy required.

But the words "range of validity" may be used in another sense. When two stations, *A* and *B*, are situated so far apart or — what amounts to the same thing — are in such different microclimatological provinces that the observations of *A* and *B* differ substantially, these differences are not of a random nature. Station *B* may perhaps many times be warmer, much colder or more moist than *A*, but the deviations group themselves according to definite laws, which are based on the physical nature of the atmosphere and the soil. These are microclimatic laws. If they are known, then the relations of the various meteorological elements at stations *A* and *B* to each other can be discovered. Microclimatology in turn now makes it possible to draw conclusions as to meteorological conditions at one place by a study of known conditions at a neighboring place.

Instead of expanding the station network by the installation of new stations we have an expansion of the useful range of each station by greater knowledge. Microclimatology even today is frequently called upon to furnish information as to the climate of an unfamiliar locality. Let us mention here a few precepts which in such a case will aid in arriving at a practical and reasonable judgment concerning the unknown microclimate.

The first thing to do, naturally, is to consider the macroclimatic relationships of the nearest observation points. They always furnish the essential basis for all microclimatic studies.

We next determine radiation relationships at the unknown place. In mountainous country they play a deciding part. To illustrate the procedure we shall refer to an investigation of this sort which F. Lauscher (487) made at the climatic station of Lunz and which represents the finest and most creative sort of work of its kind.

Radiation depends first of all on the macroclimatic radiation factors which are in turn dependent on altitude, temperature, atmospheric humidity, cloudiness, amount of turbulence, etc. and which are uniform over a wide area. Local effects are: 1. Albedo of the ground, for which the table on p. 129 gives an approximation; 2. Direction and inclination of slope, concerning whose sunniness the necessary comments have been made in Chapter 21; 3. Shading by surrounding mountains, forests, buildings, etc., of which we shall now speak.

Using a theodolite, we determine the natural horizon, in doing which we measure azimuth and angle of elevation of all heights and depressions. The result is plotted as shown in Fig. 118, which is a reproduction of four examples according to F. Lauscher.

The method is most clearly understood by reference to the upper left-hand view. The outer circle represents the horizon; the middle of the circle represents the zenith. Between horizontal and zenith the latitudes of 30° and 60° are drawn at equal distances. The sun's path is shown as of June 21st, the equinoxes, and Dec. 21st. The hours are marked on the sun's paths and at certain points connected by dotted lines.

In Meisterau, which lies high upon the Dachsteinkalk Plateau, the natural horizon is restricted only in the northeast where the edge of the plateau is somewhat elevated. Toward the west and northwest the view across the plain goes even below the horizontal.

The Gstettneralm (upper right) lies at the bottom of that great sink hole whose unusually low night temperatures have already been mentioned. (Compare Fig. 89). Consequently the horizon is quite uniformly restricted in all directions. Mitterseeboden at the lower left lies in a narrow north-and-south valley and therefore has a free horizon only toward the valley ends. Toward the east and west the outlook is hindered by the mountain sides up to a 30° elevation. The station of Höhersteinschlag at the lower right is situated in a clearing in the midst of the Hochwald and furnishes an example of an exceptionally well shaded station. In this case it is the surrounding mixed forest which furnishes the shade.

The degree of screening of the natural horizon can be made into a formula by means of which different stations can be easily compared. There are three methods used.

1. Let h be the angle of elevation by which the natural horizon is higher than the plane horizon. If we find the mean of the h values obtained from measuring in all points of the compass, we get the average screening angle (h_m). In practice it is enough to determine

h for the eight main directions, and then average these eight. For the four stations named in Fig. 118, the mean screening angles are: 4.0, 16.6, 30.5 and 49.0.

2. The solid angle of free sky is obtained as a percentage of the hemisphere (ω). On a perfect plain $\omega = 100$. When the screening

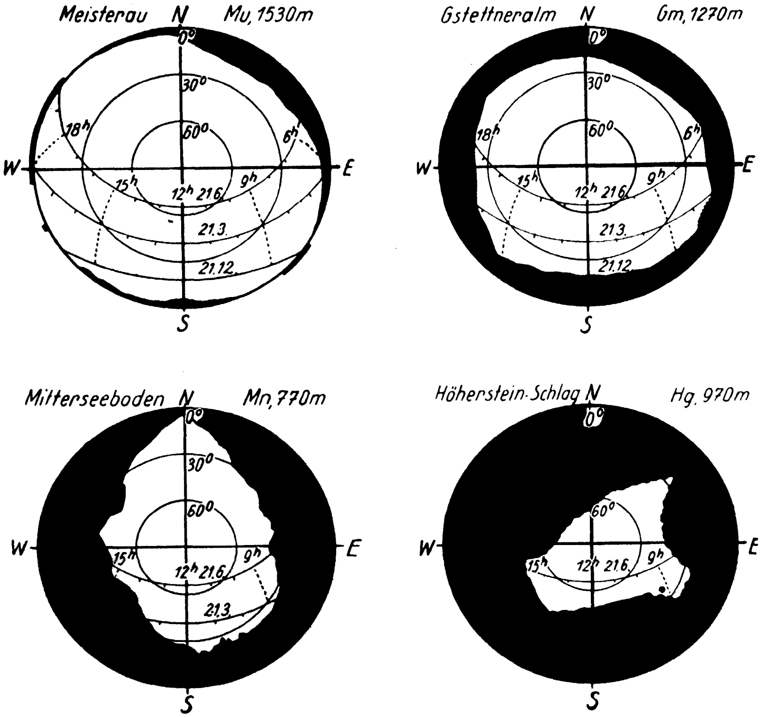

FIG. 118. Different constrictions of the horizon chosen from four of the Lunz observation stations

angle is equal on all sides $h(h = h_m)$, the solid angle $\omega = 100 (1 - \sin h)$. If the natural horizon goes up and down, ω cannot be calculated from h_m, but the calculation for each of the eight directions must be carried out separately and these partial results averaged. For the four stations mentioned above, $\omega = 93.2$, 71.5, 49.8 and 26.6.

3. Recently, F. Lauscher has proposed the "amount of perfectly diffuse radiation" (D) as the best measure of horizon screening. In obtaining this it is assumed that the radiation from all unscreened

parts of the sky is equally intense. The quantity D then gives the amount of diffuse radiation from the open sky which reaches a horizontal surface, as expressed in percentage of diffuse radiation on a horizontal plane when the horizon is entirely open. The quantity D is better than ω, because D takes into consideration that the parts of the sky near the horizon are less concerned in radiation exchange than are those near the zenith. The quantity D is calculated as $100(1 - \sin^2 h)$. For the same four stations, it equals 99.5, 91.8, 74.2, and 43.0. Naturally the difference between stations is less with D than with ω.

From diagrams similar to Fig. 118, if they are laid out on equal scale, it is possible to determine at once how long the sun shines at each station on the three days mentioned. Assuming a cloudless sky, we can then find the number of hours of sunshine resulting therefrom.

TABLE 39

For the station	On June 21st	At the equinoxes	On Dec. 21st
Meisterau	14.7	11.8	8.2
Gstettneralm	12.0	9.1	1.2
Mitterseeboden	7.4	5.1	0.8
Höhersteinschlag	6.9	0.7	0.0

The local differences in duration of sunshine are therefore extraordinarily varied. They can now also be measured by the "day-protractor" of Wilh. Schmidt (493), or the simple altitude finder of W. Kaempfert (481a).

For heat supply, however, the intensity of irradiation is much more important than duration of sunshine. We must consider the fact that restriction of the horizon always screens the sun in the morning and evening hours when its intensity is least. Consequently the difference between the four stations with respect to the amount of radiant energy received is less than with respect to its duration. If the sun is hidden half the time behind the mountain horizon the amount of irradiation is reduced, not to 50%, but in winter only to 70% and in summer only to 75%, according to Lauscher.

After radiation relationships, the next most important element to investigate is the *wind*. The less the local wind movement and convection, the more closely the microclimate follows the given radia-

tion pattern. The essential points to consider in judging it are the macroclimatic wind relationships (prevailing direction, frequency of wind forces), the topographic position (peak, saddle, windward slope, etc.) where special attention must be given to local winds (Chapters 20 and 24), restriction of the horizon (wind protection by surroundings) and the roughness of the surface.

Another good method of judging the microclimate of an unfamiliar place is by test measurements. For this we need an Assmann aspiration psychrometer and an Horn hand anemometer, which gives direct measurement of wind velocity. For the measurements of a clear day should be chosen and an hour when the meteorological elements are not changing rapidly—either early afternoon, very early morning, or late evening. Then the observations made at various points can be compared without too great errors. As a precaution, it is well to take the measurements in figure-of-eight loops so as to get measurements from one or several places at different times and so to be able to relate all measurements to the same moment. (See Chapter 38 as to the use of the research auto as a microclimatological aid.)

At each place observations are made of air temperature, air humidity and wind force preferably at breast height and also at about 10 cm above the ground in the manner advised by J. Bartels (*160*):—One goes forward slowly with the Assmann psychrometer, its clockwork running, holding the aperture constantly at the desired height above the ground. Incidentally, in such measurements, all hints are to be observed which are offered by the nature, composition, and condition of the plant cover. It has also been mentioned that valuable conclusions may be drawn from the presence of snow, frost or ice formations.

Such studies as those here proposed are of particular value in forming independent judgments. In recent literature there are fine examples of how one can evaluate such "temperature hikes." The pioneer work of Gregor Kraus (*12*) on the climate of restricted areas resulted from walks and observations in the country. Chas. F. Brooks (*474*) in the United States has reported his experiences with geography students who regularly made such experimental measurements as part of their school work. W. Hartmann (*480*) made temperature measurements on a journey over the Arlberg road. Local variations of radiation in the mountains have been observed by F. Lauscher, F. Steinhauser and M. Toperczer (*488*). F. Lauscher (*486*) described other journeys of similar nature.

The best information as to the range of usefulness of meterologi-

cal stations is certainly afforded by auxiliary networks which have been established to investigate microclimatic differences.

Wilh. Schmidt, in cooperation with H. Gams, W. Kühnelt, J. Furlani and H. Müller (*491–494*) established a network of, at first, 13 and later, 23 microclimatic stations in Austria, for the study of bioclimate. The stations were located along the northern border of the high Kalk Alps, at altitudes between 610 and 1780 m, in the neighborhood of the Lunzer Untersee. This network can serve as a model. We can only hope that the results are given sufficient publicity. In Upper Bavaria R. Geiger (*179*, *180*) operated a series of stations from 1923 through 1927 for the study of air layers near the ground. The 99 stations on the Gross Arber (*455*) have already been mentioned. On the Karst plateau of the Bükkgebirge in northeastern Hungary, F. von Bascó and B. Zólyomi (*473*) erected seven stations and carried on observations there during the summer of 1934. The stations were distributed over 4000 sq meters of the plateau at altitudes between 761 and 783 m msl. Tinn (*499*) has compared five stations in the Nottingham district of England on the basis of several years' observations. Several other examples have been mentioned in previous chapters. Altogether they furnish plenty of material for study on the question of the useful range of meteorological stations.

SUPPLEMENT

The Microclimate of Caves

There is one topographic feature whose influence on microclimate has not thus far been mentioned. This is a cave, whose climatic relationships are of interest not only as giving further information about the cave itself, but also on account of its being the natural habitat of many animals.

The microclimate of caves is, first of all, a ground climate. It is characterized by high atmospheric humidity and slight fluctuations of temperature. Caves may best be classified as having one opening or several. In the former the air is quite at rest, and the microclimate is of great uniformity except near the entrance where it is transitional between open country climate and ground climate. If the cave leads downwards from the single opening, the cold air at a certain season falls into the cave and remains there. Such caves are called simply "cold storage" or "static caves." In caves which are open on more than one side there are often uniformly high wind

velocities, since narrow passages allow equalizing currents between warm and cold parts. Such caves as these are called "wind pipes" or "dynamic caves."

The cave at Jenin in Palestine of which a longitudinal diagram is reproduced in Fig. 119, may serve as an example of a cave open on one side. P. A. Buxton (*501*) measured temperature and humidity

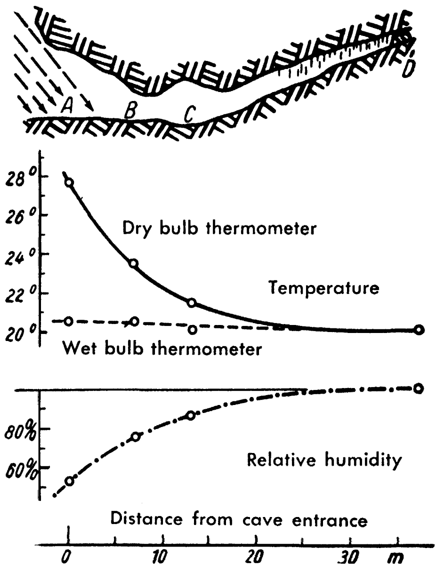

FIG. 119. Temperature and relative humidity measurements in a single opening cave. (After P. A. Buxton)

in it about midday on June 7, 1931. The data from four measuring places are given in the lower half of Fig. 119. At *A* where the daylight penetrates and where a man could stand upright the air showed the characteristics of the hot and dry outer atmosphere. 7 m from there, from point *B* the cave became smaller so that one must go on hands and knees and daylight diminishes. While the wet-bulb temperature remained practically constant, that of the dry bulb approached it. At 20 m from the entrance the air was saturated and from there on the microclimate remained constant. At *B* there was a pool in which frogs and the larvae of water insects were found. Measurements by the same author in many similar caves showed that within them the daily fluctuation of the meteor-

ological elements was below the normally required accuracy of measurement.

W. Paulcke (*506*) in 1932 investigated a cave 21 m deep, 1.2 m wide and 1.9 m high placed like a gallery in the glacier ice on the Jungfraujoch. At the entrance to the cave the temperature had a winter average of $-12°$. Consequently the temperature of the whole cave was below the freezing point but rose to $-4°$ in passing from the entrance to the inside. The vapor pressure (over water) amounted to 1.8 at the entrance and 3.4 mm at the innermost part. The super-saturation with reference to ice was 11% at the entrance and 3% at the inner end (according to information furnished by letter). There was cave frost on the walls, consisting mostly of hollow prisms near the entrance with cup-shaped crystals and leaf-shaped ice forms farther in. The various forms are described in Paulcke's wonderful book, with illustrations and explanations.

H. Mrose (*504*) has studied the temperature relationships of the "Eisbinge" at Platten in the Sudeten district. This is a cleavage cave which contains ice the year round. It is open at the top, 1 m wide and 20 m deep and is situated in the Erzgebirge at an altitude of 1000 m msl. Mrose calls it a "sock" cave since the cold air falls into it from above but cannot escape. What cave experts call "cold storage" caves are sock caves, also. In damp summer weather a thin layer of fog, 5 to 10 m deep, appears over the glacier snow within, as far as exchange of air with the exterior extends. The average annual temperature of the rock at this altitude amounts to $+4°$. At the end of winter therefore, in spite of the sock cave acting like a frost hole, the snow soon begins to melt clear to the bottom of the cave. However there is so much hindrance to the movement of heat from above and the temperature difference with respect to the surrounding rock is so slight that it takes three fourths of the year before the melting of the 1½ m winter snow is completed. By this time the first of next winter's snow has arrived so that the glacial snow never leaves the bottom of the cave.

R. Oedl (*505*) has described as follows (somewhat condensed) the caves or "wind tunnels" which have several openings: "'Wind tunnels' are all those caves which have more than one exit, so that an air circulation results in them on account of temperature differences between the cave air and the air outside. In most cases these wind tunnels have one lower entrance in the side of the mountain and another entrance into a more or less horizontal system of passages, domes and labyrinths. From these there are flues branching off — almost vertical, circular pipes which lead upward to the sur-

face of the mountain and at their exit end in earth funnels—on high plateaus, in snow funnels or little sinks. The so-called "world of ice giants" in the Tennengebirge may serve as a model wind tunnel. Passageway caves with only two openings such as we find in the huge Frauenmauer caves of Steiermark and the Mammuth cave of Dachstein are true wind tunnels with a strong air current although their entrances differ only slightly in elevation.

The alternation of air currents is a peculiarity of wind tunnels. In warm weather, when the air outside is noticeably warmer than that within, the cold and therefore heavy inner air falls out the lowest opening sucking outside air in at the upper opening; this is cooled in turn by the cave walls. In the "world of ice giants" this process is intensified by the fact that at the time of snow melting, and during periods of heavy rain, a great amount of water passes through the plateau gorges, carrying outside air with it. This is strongly cooled in the snow funnels which at this altitude easily persist throughout the whole summer, so that I have never encountered a temperature higher than $+2.0°$ in the inner cave system of the "world of the ice giants." Here therefore the geothermal stages are completely done away with to a depth of almost 800 m.

In winter, when the outside temperature is very low, the relatively warmer cave air within the mountain will rise and escape by the upper openings while cold winter air is drawn in at the lowest entrance. Hence ice formations in wind tunnels (in case percolating water and snowmelt can enter) are always found in proximity to the lowest openings. In the winter of 1921–22, for instance, a minimum of $-10°$ was recorded in the Eisriesenwelt at a distance of 600 m from the entrance. It is easy to understand that here almost 2 km of passageways are constantly coated with ice."

H. Oedl has made several hundred observations of temperature and humidity in the Eisriesenwelt at all seasons and has compared them with data from other caves. The conclusions stated here are those given in the summary of H. Oedl (505) and in the other works mentioned in the literature cited.

SECTION VI

THE INFLUENCE OF PLANT COVER

The living plant in its existence and growth is fitted by climate to its environment. One of the most important factors of a habitat, therefore, is its climate. It is a combination of macroclimatic and microclimatic features.

Plants, as living organisms, possess a peculiar heat and water economy. Along with this they exert a reaction on the microclimate of their environment. But as they grow, they change their size and form. In this way they affect the heat and moisture content of the soil in which they stand and the air into which they extend. There is, of course, an interaction between the plant, which depends on the climate of its habitat, and the climate, which is partially dependent on the plant.

The influence of plants on the climate of their environment increases with their size and with the number of its fellows. At first it is exerted in the realm of microclimate exclusively. But it gradually expands beyond the microclimate to macroclimatic dimensions, as R. Geiger (599) has pointed out in greater detail in a survey of the interaction of weather and forest. It is no longer a matter of indifference to a country and its macroclimate, whether it be wooded or unwooded.

The law of interaction of plants on their environmental climate leads to the term "plant climate" (532,4). It would be more accurate to speak of a "climate of a planting," or a "vegetation climate" (6). If general use is made of such designations, they should include all relations of the plant world and the habitat climate. The word "plant-climate" cannot be limited, as seems almost the case with E. Tamm (545), to 2-meter high forms of vegetation which are interesting to agriculture.

The investigation of the interaction between growing plants and microclimate considered as environmental climate is of great practical significance. As we gaze over the landscape in our latitude we see the earth normally covered by plant communities. Fields and gardens afford us nourishment; the forest, one of the most important and versatile of raw materials. In agriculture and forestry, in gardening and viticulture, the first care of the grower is for the

young plants, which, on account of their tenderness, are particularly sensitive to weather conditions and yet in their youth are especially tried by the extreme conditions of the microclimate near the ground. Consequently increasing attention is being paid in these days to precautions in the culture of field and forest which will foresee the habitat climate of the young plants, and to how such care along with the growing plants may influence their environment.

This sixth section is devoted to a description of the altogether attractive, but not easily fathomed, variable relationships of plants and microclimate. They will be best appreciated if we first take the plants by themselves, without reference to the air which bathes them, and ask the question, how they as living organisms react to meteorological processes. Let us begin our study with the heat economy of plants.

CHAPTER 26

The Heat Economy of Plants, and Plant Temperatures

By day plants undergo heat irradiation from sun and sky; by night they radiate heat outward. Part of the incoming radiation which falls on a deciduous leaf is reflected at the leaf surface; part penetrates the leaf and is there used to raise its temperature; another, and usually smaller, part passes entirely through the leaf, emerging from its shaded side. It is necessary first of all to comprehend the part played by each of these three processes. A number of botanists, A. Seybold in particular, and many meteorologists have studied the radiation economy of leaves and have furnished us a fairly good idea of the process. Br. Huber (*514*) is one whom we can thank for an excellent summary of the whole heat economy of plants. R. Orth (*521*) recently has surveyed the work of the Seybold school.

We begin with the reflection of radiation from leaves. It is a function of wave length. To understand reflectivity we make use, as before, of the albedo, which is the reflected radiation expressed as percentage of the incident radiation. In considering reflection from the bare ground we differentiated three spectral ranges and now do likewise.

On the short-wave, or ultraviolet, end of the spectrum (wavelengths below 0.36 μ = 360 mμ) the albedo of living leaves is small; it is less than 10. K. Büttner and E. Sutter (*307*) found a value of only 2 on a sand heath. Plants behave, accordingly, like sand and earth.

In the visible spectrum from 0.36 to 0.76 μ, where we recognize radiation as light, since it is visible to the human eye, the albedo of green leaves lies between 8 and about 20. On the white surfaces of panaschich leaves it reaches the exceptional value of 60. In the table given in Chapter 13, an albedo of from 5 to 18 was given for the forest while from 15 to 30 was given for fields and meadows. These figures fit in well. Normally, then, even in the visible portion of the spectrum, only one fifth, or at the most, one fourth, of the light falling on a leaf is reflected.

It is otherwise in the long-wave, infra-red portion of the spectrum, with wavelengths over 0.76 μ. As early as 1925 A. Ångström (*260*) showed that the albedo amounts to 44, which is considerably higher. The accuracy of this figure is directly ascertainable if one uses differ-

ent filters in photographing a landscape containing trees. Such filters allow only definite bands of wavelengths to pass, and of course correspondingly sensitive plates must be used. In 1930 E. von Angerer (*510*) published such photographs. In the infra-red photo the trees in a landscape, which normally appear dark, are light—almost white—a sign that they reflect much radiation.

Living plants, as a consequence of what has been said, have a reflectivity highly dependent on wave length—in contrast to bare ground. F. Sauberer (522) carried out comparative measurements of a meadow with grass 12 cm high, and a concrete pavement. The result is reproduced in Fig. 120. The solid curve represents the

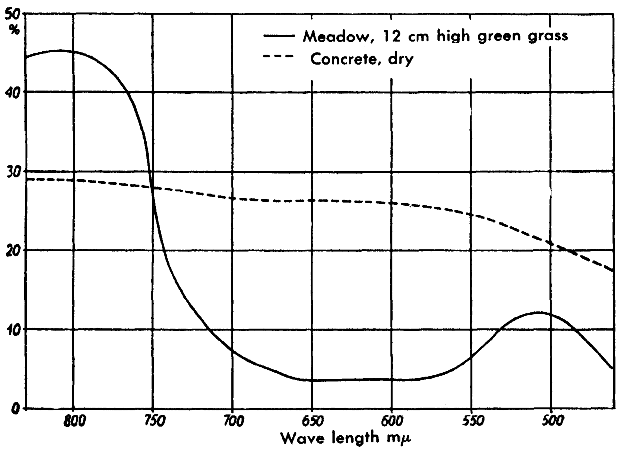

FIG. 120. The reflection from the surface of living plants (continuous line) and a dead surface (broken line) in relation to the wave length. (After F. Sauberer)

meadow. It shows a weak maximum of reflectivity at 500 mμ (in the green) and a very strong maximum at 800 mμ, which is far into the infra-red portion of the spectrum. The albedo here is 45, which is in good agreement with the measurement of A. Ångström. Concrete behaves differently, its reflectivity decreasing gradually as the wavelengths shorten.

As we pass still further into the infra-red, the albedo of plants seems to decrease again. K. Egle (*511*), for the green leaves of five different plants, found values from 33 to 49 (averaging 42) in the neighborhood of 1.0 μ while around 2.4 μ the values were between 5 and 16 (averaging 9). Mention should probably be made here of the measurements of G. Falckenberg (*269*) who, for the wavelength

region $\lambda_{max} = 10\ \mu$ ascertained an albedo of 5 for zonal leaves of pelargonium, and 4 for pine needles.

Surveying the data up to this point, we can represent it in the following table:

TABLE 40

Spectral range	Wave lengths in μ	Albedo of leaves and plants
Ultraviolet	below 0.36	below 10
Visible light	0.36–0.76	8–20 with maximum at 0.51 μ
Infra-red	0.80	45 (maximum)
	1.0	42
	2.4	9
	10.0	5

This spectral distribution of reflectivity influences the heat economy of the plant. The less the reflection, the more radiation the plant absorbs in the range in question. In the range of wavelengths in which the sun radiates most of its energy, the plant is susceptible to heat radiation. In one part of the long waves, however, the reflectivity (and, as we shall see later, the transmissivity also) is greater — the absorption correspondingly less. According to Kirchhoff's law, for a definite wavelength and temperature the ratio of absorption to emission (outward radiation) is constant. In waves of about 0.80 μ where plants absorb little, they also emit little. Long waves, however, as already stated, are the range in which nocturnal outward radiation at low temperatures proceeds — the range which the ground and plants of the earth use, in comparison with sun temperatures. It is consequently not to be concluded, as A. Ångström (*260*) believes, that a plant cover possesses in selective reflectivity or absorptivity a certain self-protection against nocturnal loss of heat by radiation. It will take further measurements to give assurance on this point.

Plant leaves also possess a certain amount of transmissivity for radiation. This can be directly observed in the midst of a dense deciduous forest in so far as the visible spectrum is concerned by the dim green light. The permeability (or, less aptly, "transparency"), which physicists and meteorologists call "transmissivity," and which botanists designate also as "diathermance," varies, like the albedo, with the wave length. In general a high albedo corresponds to a

high coefficient of permeability. By the latter term we mean the percentage of incident radiation which the leaf transmits.

In the short wave range permeability is small — less than 10, as is the albedo. In the visible spectrum it varies from 5 to 20 with a weak maximum at from 0.55 to 0.58 μ, in the yellows and greens. The eye, which is most sensitive to green, perceives the light in a forest as green. There is, however, a very strong maximum in the infra-red, at about 0.8 μ. Fig. 121, which is taken from the measurements of F. Sauberer (522) shows how abrupt the increase of permeability is

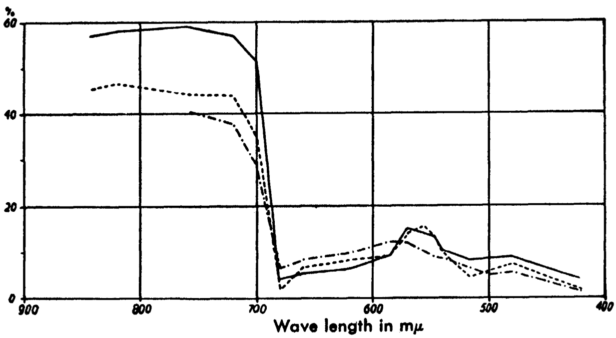

FIG. 121. Radiation permeability of three different leaves in relationship to wave length. (After F. Sauberer)

at this point. The permeability values are given in relation to wave length, the solid line representing a young leaf from a red beech; the dotted line, one from a primrose, and the dot-and-dash line, one from a hellebore. If our eyes were equally sensitive to all wave lengths, the depths of the forest would appear infra-red to us, rather than green. K. Egle (*511*), who measured the wavelengths of 1.0 and 2.4 μ, found an average permeability of 47 and 25%, respectively.

While the reflected radiation is partially diffuse (non-directional) and partially directed, the penetrating radiation is entirely diffuse. It should be mentioned that, according to F. Sauberer, it makes a difference whether the radiation strikes the upper or the lower surface of a leaf. For example the index of permeability of a white poplar leaf was 22 when radiation fell on the upper side, but only 15 when it fell on the lower side.

Within a forest, radiation is not only weakened but altered in its spectral composition. We shall have data on this point to offer in Chapter 30, which deals with radiation relationships in a forest.

Forest shade, consequently, is different shade from that which is observed on the north side of a high wall which shuts off the sun. Diffuse sky light is always particularly rich in short-wave radiation (blue sky). This latter kind of shade A. Seybold (*523*) proposes calling "blue shade." Considering the maximum transmissivity of leaves at 0.8 μ, the corresponding name for forest shade would be "infra-red shade"; it is better to stick to the way it looks to us and call it "green shade." In botany the distinction is an important one for the structure of *blue*-shade plants which in diffuse skylight by the wall of a house is quite different from that of *green*-shade plants which spend their life under the leafy screen of a mixed or deciduous forest. To follow this further would take us too far into the realm of botany.

If the albedo (R) and the index of transmissivity (I) are known, we at once have the percentage of absorbed radiation (A), for $R + D + A$ must equal 100 units, or the total incident radiation. We must therefore conclude that in the ultraviolet absorption amounts to about 90% of the incident radiation, that it diminishes with increasing wavelength, reaches a minimum of about 25% in the yellow-green and, after another slight rise, falls off to its chief minimum of between 5 and 10%. Still further into the infra-red the value of 10% is again attained at 1.0 μ, after which the absorption climbs to 65% at 2.4 μ.

While the radiation relationships of a certain place do constitute an inescapable climatic factor for bare ground (see Chapt. 36), they do not do so for the living plant. It has a great many ways of protecting itself against too strong radiation and several possibilities by which it may lessen the harmfulness of too much outgoing radiation. "Nature," says P. Filzer (*512*) "does not work by a diagram; a living substance is no stiff physical system but a plastic, and can solve the same problem in many different ways."

The possibilities of avoiding excessive irradiation rest with the structure and position of the leaves. An example of this has been given by the case of the compass and gnomen plants. The profile position of their leaves in a sunny location (called the vertical position) results in the least possible surface area being offered to midday radiation. A rippled leaf surface hinders the whole leaf from receiving the maximum radiation no matter what the sun's position. The albedo varies with changing leaf color. In the case of the cactus, the often too violent impact of radiation is partially broken by tufts of thorns which lie parallel over the leaf surface, or felt-like

cushions of a similar nature. The part played by the anatomical structure of the plant belongs to the province of botany. Bruno Huber's summary (*514*) of this subject may be consulted.

Of more interest perhaps to meteorologists is the variable lighting of leaves. By this we mean the ability of leaves to initiate variations in the radiation balance by means of movements of their leaf organs. There are leaves of certain living plants which, after 15 minutes of irradiation by an electric heater, will assume their daytime sleeping position, in which, by the action of their peculiar leaf joints, they are able to crease their surfaces and so lessen their effective heat-absorbing area. In their nighttime sleeping position too, the leaves stand almost vertically, perhaps in order to reduce nocturnal radiation losses. O. W. Kessler and H. Schanderl (*517*) have published some fine photographs of the white melilot (melilotus albus) with its leaves in different positions, to which we have already referred. In the dry Mediterranean district and on tropical steppes there is said to be noticeable "a peculiar change in the appearance of the landscape according to the hour of the day." It is apparent that this must react on the microclimate.

In addition to radiation, there are other factors which affect the temperature of plants. The respiratory heat of plants as a result of metabolism inclines to a rise of temperature. Normally it may be disregarded, and only in the sprouting and blooming of the higher plants does it attain a magnitude worthy of consideration. Even then it is most limited. Evaporation (transpiration of plants) tends to cooling. Since for every gram of water given off, there are from 570 to 600 calories required of the plant according to the temperature, this heat loss may reach considerable proportions. Finally there is heat exchange with the surrounding air, which, for the plant, may be either positive or negative.

Taking all the above-mentioned factors into consideration, there finally results for the plant at any given moment a positive or a negative remainder, which occasions a rise or a fall of its temperature. In general, therefore, a plant, a leaf, a needle, a branch, does not have the same temperature as the surrounding air. This is a fundamental rule which one must heed carefully. In general it may be said, that the plant is warmer when the ground surface is warmer than the air layer resting upon it — when there is a positive radiation balance. This is the case during the day. Conversely, by night the plant is, for the most part, cooler than the air.

The differences between plant and air temperatures disappear,

however, if the plant is not carrying on its own radiation exchange. This occurs only when there is no such exchange in the atmosphere, to speak of — i.e., at the times of transition from positive to negative radiation balance and vice versa — at evening and morning and, secondly, with completely covered sky, rain, driving snow, fog, etc. They disappear also in the case of those parts of a plant which are screened by other parts. The inner and under parts of a tree or shrub — yes, even a small plant — in this case have an interchange of radiation only with other parts of the plant and these, in general have the same temperature. Radiation exchange with the surroundings is carried on by only the outer leaves.

This precept finds practical application in estimating frost danger. A two year old pine seedling, standing under an old-wood screen of frost-hardy birch, has about the same temperature as the surrounding air. The same plant, standing in the open nearby, will be colder than the surrounding air. The temperature difference between inside and outside is, in the case of the plant, greater than that measured in the air with the aspiration psychrometer. (See Chapter 40.)

The measurement of plant temperatures is, in itself, no easy task, because the plants to be measured must remain undisturbed in their life functions. Thin leaves, needles and blossoms present difficulties on account of their smallness. A small mercury thermometer can be used with tree trunks, thick branches, fleshy leaves and fruits. In this way F. D. Young (528) in California, for example, observed orange temperatures just beneath the skin, on the side of the fruit turned away from the tree, in order to let the fruit present their own evidence in the matter of frost danger. The oranges could be supercooled to $-4.2°C$ before they froze.

The method of quickly wrapping a freshly picked leaf about a mercury thermometer will give a rough approximation of leaf temperatures. The calorimetric method has been tried also. In this, leaves were dropped into a vessel filled with turpentine and the temperature change measured. If the specific heat of the leaves has been determined, the original leaf temperature can be calculated.

The thermoelectric method is one which is today in common use. One soldered junction of copper and constantan wires is kept at a fixed temperature by means of a portable thermos flask, while the other junction is formed into a "thermoneedle" which is inserted in the plant or pressed against it. An accuracy of $0.1°$ can be attained without difficulty.

Ordinary thermoneedles, however, are not fine enough to prevent

radiation errors of 2 or 3° C in sunny leaf surfaces. Furthermore, it is the portion of the soldered joint nearest to the conducting wires which is most effective and this in use is often outside the leaf, bud, etc. A. Mäde (*519*) who worked this problem out carefully, has recently successfully adapted the Albrecht resistance thermometer to the measurement of leaf surface-temperatures. He used a 0.015 mm platinum wire a few centimeters long. Not only can an accuracy of about 0.2 C be realized, with proper handling, but the apparatus has the further advantage of being capable of recording. The temperature records shown in Fig. 123 were obtained with this apparatus. What excellent results can be obtained from its use is attested by the detection of a pool of cold air on the upper surface of a radiating castor-oil leaf by H. Ullrich and A. Mäde (*525*). The leaf was decidedly arched and formed a little bowl whose rim was 1 cm high. The tiny drop of cold air reached just to this height.

Let us now discuss what more can be asserted as to the temperatures of plants, particularly in relation to air temperature.

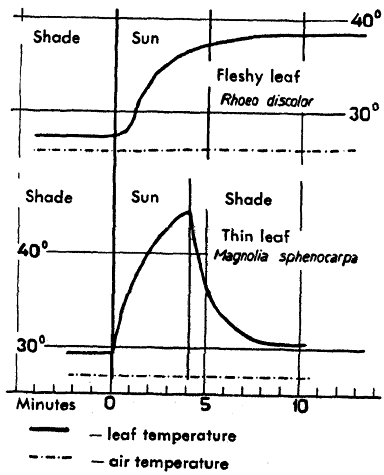

FIG. 122. Reaction of leaf temperature to sudden sunning

Every leaf has a certain thermal lag. If it is exposed to the sun, it takes some time, perhaps 5 or 10 minutes, before its temperature has risen to such a point that the heat lost to the unaltered air equals the heat gained by the absorption of insolation. Fig. 122 shows the temperature curve of two different leaves which were suddenly exposed to the sun and as suddenly shaded. The observations were

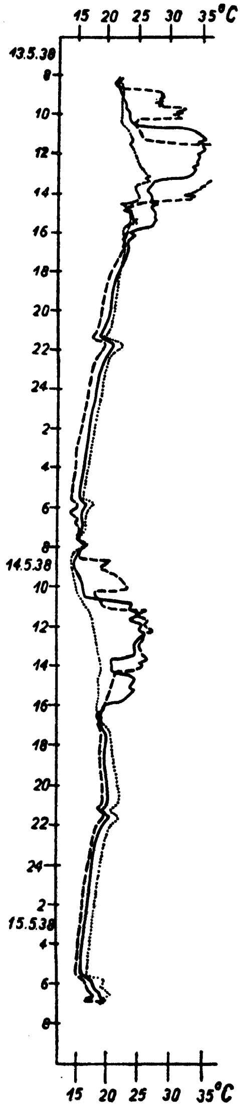

FIG. 123. Registration of leaf surface temperature and (dotted line) air temperature for two days. (After A. Mäde)

made by A. M. Smith (*524*) in 1906 under the tropical sun in a garden at Seradeniya, on the island of Ceylon. The current air temperature is represented by the dot-and-dash line. At the moment of exposure to the sun, the temperature of the thin leaf rises immediately; that of the fleshy leaf rises only after a short interval, quickly at first, then more slowly. The temperature approaches the well known Newton curve of equilibrium, which has been described above. The difference between air and plant temperature reaches the significant amount of 11° in the case of the fleshy leaf and still higher for the magnolia.

Fig. 123 shows a continuous record of the true leaf surface temperature of two different plants over a period of two days. It was published at Muncheberg by A. Mäde (*519*). The solid line refers to a fleshy, hard leaf of Bilbergia nutans (a hothouse plant of the pineapple family). The broken line refers to the thin, deciduous

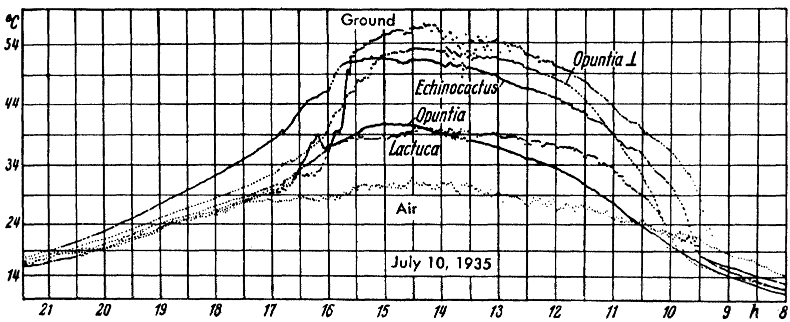

FIG. 124. Temperatures of the air, the earth's surface and different plants. (After Br. Huber)

leaf of Plectranthus fruticosus (cockspur, a small shrub of the labiaflora). The concurrent course of the true air temperature is shown by the dotted line. During the middle of the day the leaf surfaces are 10° or more warmer than the air. The greater lag of the fleshy leaf is discernible in the delayed rise and fall of temperature; the greater mass, in the lower maximum. When the radiation balance is negative, the leaf surfaces are cooler than the air, the thinner one correspondingly cooler than the thick one. Splendid temperature records of a peach twig are to be found in another paper by A. Mäde (*518*).

Similar measurements by H. Ullrich and A. Mäde (*525*) indi-

cated a difference of more than 1° between sunny and shaded portions of a leaf only 2 cm apart.

At Rathen in the Elbsandstein mountains, Br. Huber (515) made simultaneous records of surface, air and plant temperatures in a wind-shielded SSW trough. He used thermocouples which registered on a Hartmann and Braun multiple thermograph. Fig. 124 gives an example. It shows, what Br. Huber found to be a rule of general application, that all the plant temperatures lay between the air temperature and that of the ground surface. Projecting parts of plants attained about 1/3 of the temperature excess of the dry ground; parts near the ground, from 1/2 to 2/3 of this temperature. The record of Lactuca in Fig. 124 is an example of the former,

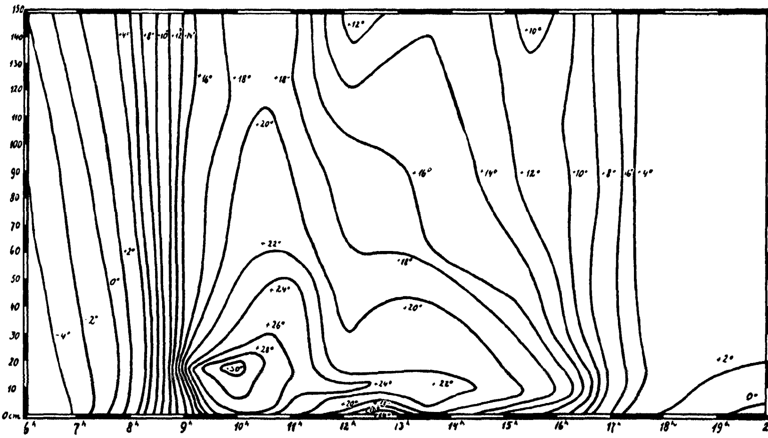

FIG. 125. Course of temperature in a green alder twig which penetrated the snow cover

while that of a Carnegia (barrel cactus), which in Fig. 124 is erroneously labeled "Echinocactus," represents the latter. Nearby the Opuntia surface-sprout, which was growing in a naturally vertical position, and whose temperature followed a course similar to that of the Lactuca, an Opuntia sprout was placed artificially perpendicular to the sun. The corresponding record is designated Opuntia ⊥ in Fig. 124. The temperature of this sprout closely approached that of the ground surface.

Br. Huber has found a maximum temperature of 56° for living plants in a sempervivum with air temperature of 35°. Temperatures of 50° have been repeatedly obtained by different observers.

Finally it should be pointed out how the radiation and temperature conditions of the air near the ground determine the temperature of the plants growing in it. Towards the end of the winter of 1933, while snow was still on the ground G. & P. Michaelis (520) made some thermoelectric bark temperature measurements of a green alder twig at Allgäu in the little Walser valley at 1670 m msl. The results are shown, by means of isopleths, in Fig. 125.

March 16, 1933, was slightly cloudy; the air temperature ranged between −2 and +4° C. The temperatures in the bark of the green alder twig fluctuated between −4 and +30° C. The greatest temperature fluctuation would be looked for at the snow surface, on

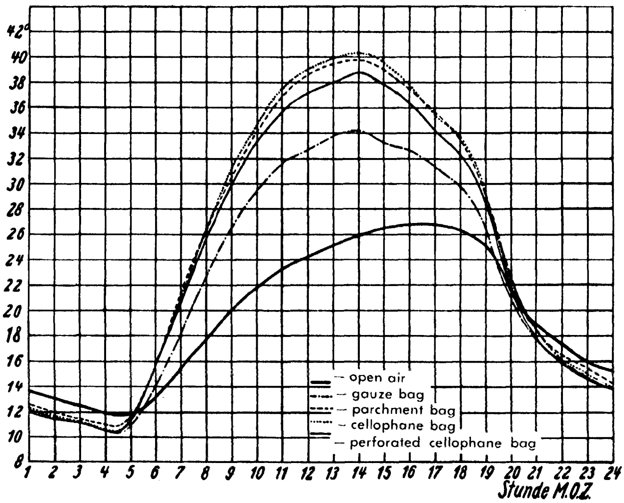

Fig. 126. Course of temperature on five clear days in bags which are used for biological experiments

account of radiation. The cooling effect of the snow through conduction, however, raised the point of maximum fluctuation of the twig temperature somewhat above the snow level; at least as long as incoming radiation prevailed, the twig was overheated. At 10 A.M. the temperature maximum was at a height of about 15 cm, but when the snow began to melt right by the twig, the maximum moved downward. At night, when the counter-radiating twig had almost the same temperature as the snow the minimum remained at the surface.

The following microclimatic phenomena are presented as a supplement.

In gardening experiments, blossoms are often enclosed in parchment or gauze bags or the like in order to prevent their random pollination by wind or insects. It is self-evident that such covers considerably change the radiation and heat balance of the flowers and thus their temperature. Anyone making biological experiments with blossoms should not overlook this fact.

N. Weger (527) has studied the relationships involved in this condition. Fig. 126, which is based on mean values of five radiation days in May and June, 1937, shows the curves for the temperature in the open air (heavy line) and in bags of four different materials. During the time of incoming radiation it is as much as 15° hotter in the bags than in the open; at the time of outgoing radiation it is somewhat cooler. The temperature march in the little bags with their small volume of air follows the course of radiation more quickly than does the free air and therefore attains a maximum a good three hours sooner. The air heats up most rapidly in the transparent cellophane bags. Perforating the bags brings the maximum temperature down by 2° on account of the improved convection. The ventilation is best in the gauze bags; their overheating amounts to 6° or 7° less than in the cellophane bags.

CHAPTER 27

Radiation and Temperature Relationships in a Low Plant Cover

In Chapter 17 we spoke of plants, indeed, but only of such small ones — by reason of their youth or nature — that they could hardly alter the characteristics of the ground surface. This kind of a plant cover we called ground cover and have already said all there is to say in describing its influence on the microclimate.

Now, however, our attention is directed toward what happens when the plant stretches up into the sea of air yielded to it from the sway of the wind, and brings continually higher layers into its sphere of influence, gradually forming the habitat climate from the ground up.

The high forest is quite the opposite of the ground cover. Under the close crown of an old stand there is room for a body of air several dekameters deep, whose properties are conditioned by the stand. This is the realm of the trunk climate, peculiar to the forest. Insofar as there still is a climate near the ground, it is raised from the solid surface and re-located at the crown level. There is where radiation is absorbed and sent out, the free-air wind is retarded, and water is given off to the air as it is from the earth in the open. In place of the ground, which now lies within the forest depths, de-activated, the crown surface becomes the outer, active surface. This conception, introduced to meteorology by A. Woeikof, will give us the best idea of the interaction between plant and microclimate. We must realize, however, that the expression "surface" is no longer to be used in its old sense, but idealized, for at the top of the forest it is a space with decided vertical compartments which has taken over the role of the solid ground surface.

Between ground cover and forest we introduce as an intermediate stage the low plant cover. To this belong all agricultural crops such as grain-fields and potatoes as well as forest plantings which have not yet passed the sapling stage, all bushes, meadows, weed fields, etc. The low plant cover differs from the ground cover in that it characterizes the air space which it encloses and on its part interacts with the outer air; it differs from the forest in that it lacks the seclusion from the outside which characterizes the space within the dense crown as an independent body of air. The two following

chapters have to do with this low plant cover. Together their title should be: "Agricultural Microclimatology," were it not that on the one hand they also include problems which are important to forestry while, on the other hand, agriculture has an ardent interest in the microclimatic questions which have been described in the earlier sections of this book. The relations of forest and microclimate are to be treated in Chapters 29 through 35.

In order to depict the microclimatic relationships in and over a low plant cover, let us begin with the radiation economy.

Fig. 127 represents, side by side, an extent of bare ground and a meadow with grass 1 m high. The insolation from above is completely absorbed in the surface layer of the bare ground. In the

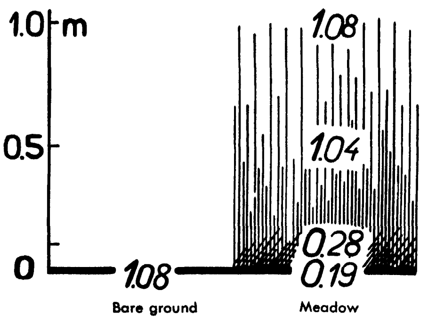

FIG. 127. Gradual absorption of radiation in a meadow. (After A. Ångström)

grass, a greater portion is caught between the blades. In the diagram, the values of insolation intensity are expressed in calories per sq cm and min. as A. Ångström (260) observed them in a field grown up with meadow grass and Dactylis glomerata. We see that at 50 cm above the ground the intensity is still scarcely weakened, but then it decreases rapidly to a fourth of its original value at 10 cm, while at the ground it is only a fifth of the radiation which falls above.

In a young elm thicket, 3 m high, which was filled with dense undergrowth and overgrown with clematis, F. Sauberer (522) observed the radiation still to be found in the first meter above the ground, using Lange resistance cells with a filter, which are especially sensitive for wavelengths in the orange. It varied greatly with the season. In June and July there was a minimum of brightness close to the ground for at this season the low early-growing plants

were fully developed. As these die down, the brightness at the ground increases. Here are some of the figures:

TABLE 41

BRIGHTNESS DISTRIBUTION IN DENSE ELM THICKET

(in % of outside brightness)

Height above ground	1	10	25	50	100 cm
July 5, 1936	0.01	0.06	0.13	0.23	2.1
July 19, 1936	0.03	..	0.17	0.41	2.2
Nov. 15, 1936	0.50	22	30	30	59

After the leaves fell in November almost a fourth of the outside brightness penetrated to within 10 cm of the ground, but only one half of one percent reached the ground. In the winter condition of the elm thicket not quite 10% reached a point 1 cm above the ground, as further measurements showed.

Fig. 128 shows the daily march of visible radiation in different agricultural crops. The radiation intensities there represented were

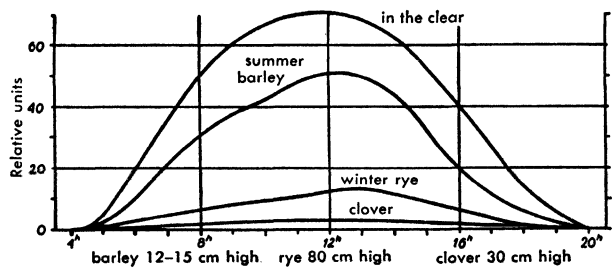

FIG. 128. Daily course of brightness on the ground in different fields on a May day. (After F. Sauberer)

measured (again by F. Sauberer) May 6 and 7, 1935, on the ground in the fields. They represent the amounts of light which are available for germinating weeds in the fields. The great difference between the vertically standing blades of the scanty barley or dense rye, and the broad clover leaves which intercept much radiation is very evident. We shall revert to this difference in considering temperature relationships.

There is also a considerable exchange of radiation within the lower plant cover, to which F. Sauberer has called attention. As portions of plants here and there are warmed by absorbed radiation

from sun and sky, this heat cannot not be passed on either by the poorly conducting plant or by the poorly conducting air. Even convection is limited on account of the enforced inertia of the air entrapped among the plants. Heat transport takes place rather by radiation which passes from the warmer to the cooler parts of the plants. Furthermore the radiation reflected from the plant surfaces must not be forgotten. The interchange of radiation, therefore, within the plant cover is very complicated and becomes still more so by reason of the selective properties of leaves, which were described in Chapter 26. As a result, not only the amount but also the nature, of the radiation within the lower plant cover is subjected to continual change.

However difficult it may be to comprehend these processes by themselves, the one fundamental fact is plain, that a plant-covered plot receives no more and no less heat than a barren plot of like size, for vegetation does not affect the intensity of irradiation. Only the portion lost by reflection can differ. Likewise the outgoing radiation from 1 sq m of plant-covered soil and the like area of bare soil by night are equal (in contradiction to the false representation in the first edition). Here, too, it is only variable absorptivity and albedo — with consequent altered power of radiation — which can make a difference, and even this is of scarcely any practical significance.

What, however, completely alters the effect of plant cover is the distribution of the given amount of heat gained or lost. While, in the case of bare ground, the whole exchange is at the border surface between soil and air, there is available in the plant cover a high vertical space instead. This distribution of the day's warmth protects from sudden heat, while the similar spread of nocturnal cold protects from damagingly low temperatures. *Plants modify the temperature fluctuation of the climate near the ground.*

With this we turn from a consideration of radiation exchange, to heat exchange. Let us begin with the temperature distribution in a low plant cover at the time of incoming radiation.

Fig. 129 represents midday temperatures in a bed of antirrhinum (snapdragon) in the summer and autumn of 1923 as observed by R. Geiger (*179*) in the convent garden of St. Boniface at Munich. The plant cover is charted schematically according to its measured height and density. The flowers with their horizontally placed leaves capture the insolation in the upper layers. The "outer active surface" and with it the temperature maximum consequently is located near the top of the plant cover. July is an exception, since in this month

the young low-growing plants are still scattered so that the heating of the open bit of ground between them determines the vertical temperature distribution.

A comparison of the July and August curves will make clear why on microclimatic grounds, young crops often do not begin to grow

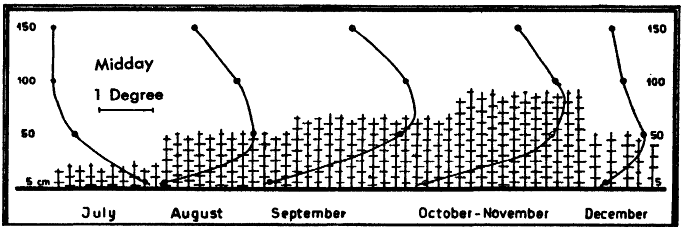

FIG. 129. The incoming radiation type in a flower bed

luxuriantly until they have "joined hands"—i.e. when the separate plants touch one another. In July (Fig. 129) this is not yet true; the sensitive young plants still have to endure the sudden midday heat of open ground. In August, however, the outer active surface

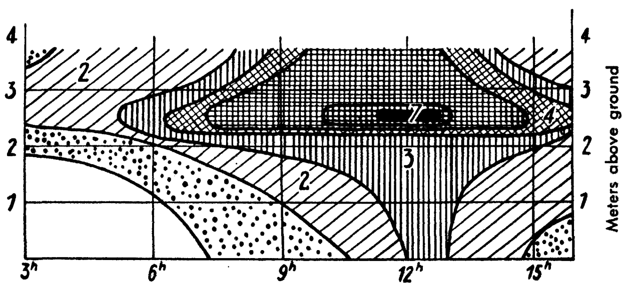

FIG. 130. The temperature unrest in a 2½ m high growth of a young pine showing external active surface layer

is raised above the ground. This ties in with the necessity of shielding sensitive newly set out garden plants in hot weather.

Fig. 130, which was published by R. Kanitscheider (533), shows how all weather phenomena act on the top of the plant cover. He took temperature readings with a resistance thermometer every 2 seconds in dense growth of ground pine on a southerly slope near Innsbruck (1600 m msl). Fig. 130 represents the result in relation to height above ground and time of day on the cloudless 28th of

July, 1931. The figures within the chart are mean differences between two successive readings in tenths of a degree. At all times the top surface of the pines is the most turbulent zone. The turbulence is greatest, not at the time of maximum temperature, but at the time of maximum radiation.

It is different with the midday temperature distribution in a plant cover consisting of vertically standing single plants. Fig. 131 gives measurements which R. Geiger (*179*) made in 1925 in a field of

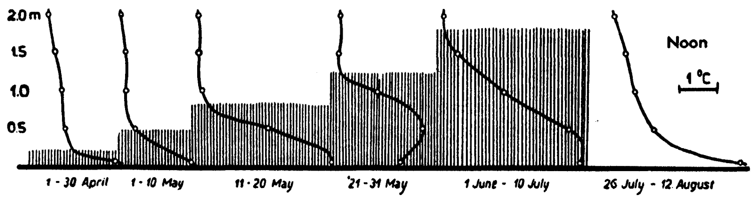

FIG. 131. The incoming radiation type in a field of winter rye

winter rye. These measurements were made on the Nederling experimental plot of the National Institute for Horticulture and Plant Protection at Munich. Until the 20th of May when the grain had already reached a height of almost 1 m, the temperature maximum remained at the ground surface, so easily could sun and sky radiation penetrate down between the stalks. Then the site of the maximum rose but still remained far below the top surface of the plants. After the grain was cut on July 26th, the normal incoming radiation of an unplanted field re-established itself.

According to the nature of the plant cover, the outer active surface either coincided with the upper surface of the plants or lay far below it. We can thank P. Filzer (529) for systematic investigations into the influence of size and density of vegetation. As an example of a horizontally distributed plant community he chose the sunflower; for one which is vertically distributed, maize. Surface area and density of the plantings were varied. Nine beds were sown with each plant. The areas of the beds were 90, 64 and 45 cm square. The density of seeding was so regulated that the distances between plants amounted to 8.6, 6.0 and 4.2 cm. As the average noon measurement on four clear days of September, 1934 he found the following temperature differences between the ground surface and a point 1 m above it (+ means the ground was warmer, — means it was colder, than at 1 m): —

TABLE 42

TEMPERATURE GRADIENT ABOVE THE GROUND AT TIME OF INCOMING RADIATION

Structure of Plant Cover	Horizontal (sunflower)			Vertical (maize)		
Density:	Large	Medium	Small	Large	Medium	Small
Large Area	−3.0	−1.8	+0.5	−2.5	−0.4	+3.7
Medium Area	−1.7	−0.7	+0.9	..	..	..
Small Area	−0.6	+0.2	+3.8	−1.2	+1.0	+3.2

The closer the plants stand and the greater the area of the bed, so much cooler is the lowest air layer during the whole day with consequent greater development of a characteristic microclimate in the plant cover. On the other hand the highest temperature occurs at the ground consistently in all cases where the density of stand is least, but with medium density it occurs there only if the bed area is small.

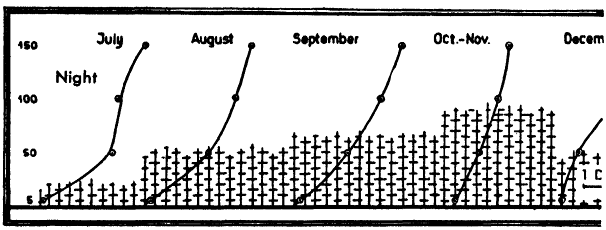

FIG. 132. The outgoing radiation type in a flower bed

At night, with outgoing radiation, the relationships are different, and to these we shall now turn our attention.

Referring again to P. Filzer's investigations they indicated no clear nocturnal relationship between temperature distribution on the one hand and the size and density of plant cover on the other. The air at night was consistently warmer at the ground than at a height of 1 m. Radiation was from the top surface of the crop as was to be expected.

Now let us return to R. Geiger's measurements in the antirrhinum bed and in the winter rye. The nocturnal curve is given in figures 132 and 133. In both crops the outgoing radiation was greater from the upper parts of the plants (which radiated freely to the cold night sky) than from the lower parts which, for the most part, gave off their heat only to the upper parts. The nocturnal cold air accumu-

lated first in the upper part of the plant cover. That is also where the lowest temperature would be found, if the cold and consequently heavy air did not sink down.

This sinking can easily take place in the flowerbed (Fig. 132) since the parts of the plants stand rather far apart, leaving plenty of air space clear to the ground. In the rye field, however (Fig. 133) the stalks below form a thick felt which slows up all air movement. Thus it comes about that in the flowerbed the daytime maximum occurs above and the minimum at the ground, while in the grain field the maximum occurs near the ground and the minimum half-way up. These conditions are significant in questions of frost protection.

For the daily march of temperature in a low plant cover, we refer to H. Berg's description (*98*). On the 6–7th of October and the 20–21st of November, 1934, he recorded the temperature and vapor

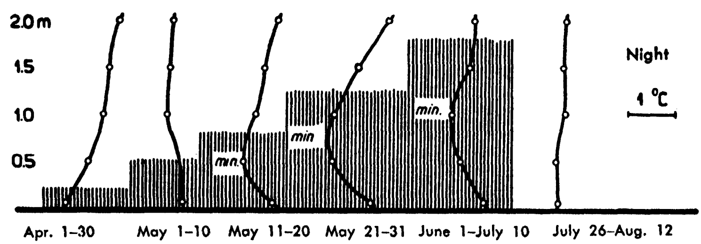

FIG. 133. The outgoing radiation type in a field of winter rye

pressure in a 10 to 15 cm calluna cover on the Bissendorf moor between 1 m above, and 30 cm below, the ground surface, publishing his results in tables and diagram. R. Fleischmann (*530, 531*) carried out various measurements in different kinds of grain fields, in tobacco and in corn and has been able to show thereby that each kind of grain has a particular kind of "species" climate. At Göttingen W. Paeschke (*561*) made short series of measurements in fallow land, in low and high grassland, in high wheat and in turnip fields with excellent physical measuring technique. As for agriculture, E. Tamm (*545–547*) at Berlin obtained most comprehensive records of all the important weather elements over a period of years. His measurements in crops of winter rye, wheat, barley, oats, potatoes, corn, lupines, hemp, soya beans and flax are unfortunately worked up according to the method of temperature summation and averages, exclusively. At the agrarian meteorology research station

of the Imperial Weather Bureau at Giessen, W. Kreutz (*536*) made a series of measurements in potatoes, flax, rape, corn, barley and wheat and has shown the manifold implications of the problem in an entirely new method of attack.

From the measurement of A. Mädes (*538*) at the research station of the Imperial Weather Bureau at Müncheberg (Mark) we offer a daily temperature curve from a stand of topinambur. The records, which were made with a radiation-shielded resistance thermometer, ran throughout August, 1935. Fig. 134 shows the temperature march for Aug. 4. (The mean values for the month of August give practically the same daily march only somewhat smoothed.) At the time of measurements the topinambur stood 73 cm high. The six points of measurement are shown, according to their height, by arrows at the right-hand end of the illustration.

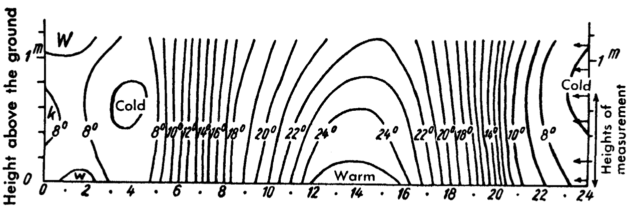

FIG. 134. Diurnal temperature course on a clear August 4, 1935, in a stand of Topinambur at Müncheberg. (After A. Mäde)

In the open planting which still allows the sun partial access to the soil, the noontime temperature maximum lies at the ground. Not until the latter half of August does it rise from the ground, as the crop thickens. A fresh wind, A. Mäde found out, had the same effect as thinner seeding. On the one case increased convection removed the excessive heat above so that the location of the temperature maximum is lowered; in the second case, it is located at the ground from the beginning, as a result of the permeability of the crop to radiation. At night the minimum is evidently at the upper surface of the vegetation. The topinambur thus behaves like the grain field in figures 131 and 133.

There is still one particular crop to consider, which depends to a great extent on the peculiarity of the climate near the ground — grapes. It was R. Kirchner (*534*) who carried out the first useful studies in vineyards of the Palatinate. They have been edited by K. Sonntag (*544*) and extended somewhat. More recent measurements have been made by N. Weger (*551*).

In the Palatinate the vines are customarily supported on wires so that they reach a height of only 70 to 120 cm and take full advantage of the sunny microclimate near the ground along the slopes. About noon on Sept. 17, 1933, K. Sonntag found the temperature depicted at the left in Fig. 135 in a vineyard at Mussbach, where the rows ran north and south. The graph at the right shows nighttime conditions. The active surface is doubly present in this vineyard. The surface of the vines heated up, as well as the ground *between*

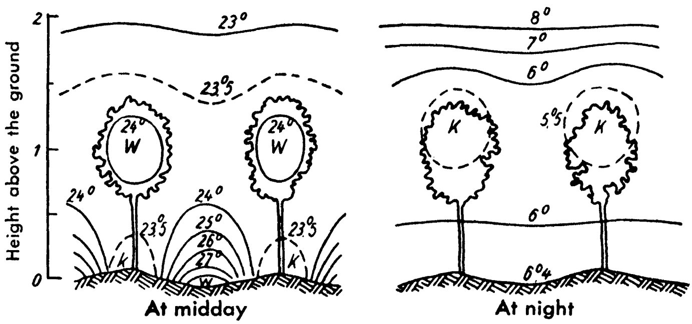

FIG. 135. Temperature distribution on September 17, 1933, by day and night in a vineyard. (After K. Sonntag)

the vines. The temperatures at the ground, however, for reasons which we have explained, are considerably higher than those of the vines. By night it is especially cold at the height of the trunk. This, as K. Sonntag remarks, is very important in the utilization of dew by the plants. Because dew is always precipitated on the coldest surfaces, the leaves are thoroughly wet at night, while the branches and ground remain dry. "Even outside the vineyard an iron bar standing on the street was dry from the ground up as high as the first branches, though covered with water drops at the height of the foliage."

All the observations made thus far on temperature relationships in the lower plant cover refer to the climatic province of central Europe. It is granted that in northern countries the utilization of radiated heat is of still greater importance. A. Wegener (550) pointed out in reference to Lundager's measurements, which were made in northeastern Greenland at almost 77° N, that the temperature in the midst of plants, as averaged from numerous summer observations, was 8° to 9° — and, in some cases, even 16° — higher than in the surrounding air.

On the other hand we have interesting relationships in the tropics, about which we are quite well informed. It appears that plant temperatures show the same features as they do with us in the summer. Careful measurements on this subject have been made by L. A. Ramdas and his collaborators, R. J. Kalamkar and K. M. Gadre (*541*, *542*) at Poona in India at latitude 18°. Fig. 136 gives an example from their work. It represents the average temperature distribution as to height for the hours of sunrise (temperature minimum) and midday (temperature maximum), at three stations

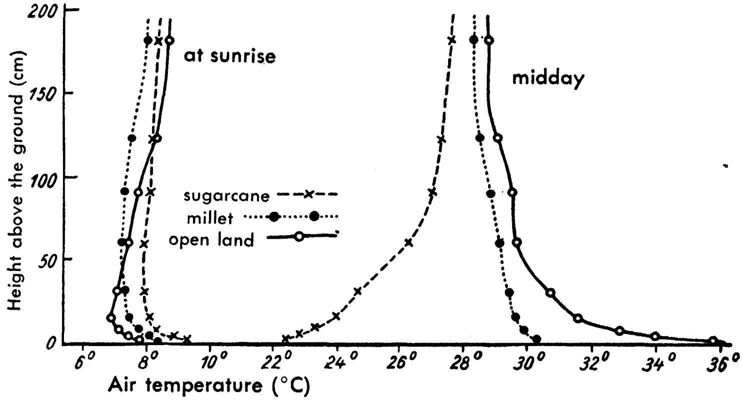

FIG. 136. Temperature distribution in a field of 2½ m high sugarcane, a field of 1½ m high millet in comparison to open land in Poona. (India) (After L. A. Ramdas, R. J. Kalamkar, and K. M. Gadre)

closely grouped. The time is the latter half of December, 1932, a period which in India is characterized by the dry northeast monsoon, which blows from the land toward the coast. The open country (solid line, with measuring points indicated by small circles) has the midday incoming radiation type developed to a marked degree. By night the lowest temperature occurs, not at the ground surface, but 15 cm above—a peculiarity to which we have already called attention in Chapter 7.

Millet (Rabi jowar) is not an irrigated crop. It stood 150 to 180 cm high at the time of the measurements. Its temperature throughout the day is lower than in the open. The difference is greatest at the shaded ground and becomes slight at the top of the grain. As the millet grows higher and denser, the upper surface of the crop, as later measurements showed, receives so much radiation that the

temperature there becomes even somewhat higher than in the open. At night the migration of the origin of outgoing radiation to the crop surface manifests itself by lower temperatures at heights over 50 cm, while beneath that height the plants gain little heat.

Sugar cane is an irrigated crop which stood about $2\frac{1}{2}$ m high at the time of measurement. The observations recorded in Fig. 136 were all made within the crop area. It is considerably cooler there than in the open; at midday the difference near the ground amounts to 14°C. Even at night it is still 1° warmer in the lower layers. Not until a height of 130 cm is reached does the cold air from the outward-radiating crop surface make itself felt.

The author calculated the following daily temperature fluctuation at the three places of observation during the period from the 4th to the 16th of December 1932.

TABLE 43

Height above the ground in cm	Average daily temperature range in °C		
	Open country	Millet crop unwatered	Sugarcane watered
183	29.8*	30.0	27.5
122	30.0	29.9	27.0
91	30.6	29.8	26.4
61	31.0	29.7	25.5
31	31.6	29.9	24.6
15	32.5	29.7	23.8
8	33.6	29.4	23.3
3	34.8	29.3	23.0
1	36.7	29.3*	22.7*

While the greatest fluctuation in the open occurs at the ground surface, this condition is reversed in the crops. At 183 cm which is still somewhat below the top surface of the crop, the outer active surface can be recognized in its temperature effect.

K. Wien (549) the German scientist who died at Nanga Parbat, made test measurements in middle East Africa. On March 31 and April 1, 1934 he carried out some temperature measurements in a young coffee plantation in the German colony of Oldiani, which is situated in 3° south latitude, at an elevation of 1730 m. The measurements were obtained at the ground and at a height of 1.5 m. Measurements were also made in a neighboring forest of fullgrown evergreens — a forest above the steppe zone. While the daily temperature fluctuation in the open amounted to 11°, it mounted to 20°

on the black one-time forest floor of the coffee plantation, since the space between the coffee shrubs was sufficient to let the sun reach the ground. In the high forest the daily range was only 8°.

H. Scaëtta (*543*) made observations in some of the tropical highlands. On June 19, 1929 he recorded the following noon temperatures at Karisimbi, north of Lake Kiwu (2° S) at 4506 m msl.

Temperature, in the free air = 5° C
Inside Alchimilla thickets = 14.6° C
In the top layer of dry soil = 16.2° C

An hour later

Temperature, in the free air = 3.5° C
" in a clump of Poa glacialis = 17.4° C
" in a dry lichen sod on a lava plateau = 19.4° C

It appears that in tropical highlands the plant cover has the same effect on the temperature as A. Wegener found in Greenland.

CHAPTER 28

Humidity and Wind Relationships in a Low Plant Cover

The first time anyone compares temperature, with a thermometer, inside and outside a low plant cover, he is struck by the greater warmth inside. Examples of this were given in Chapter 23. One reason for this is the retention of ground heat by the protective plant cover; the other is the direct addition of heat to this air-space among the plants by means of radiation which leaves, stalks or twigs absorb.

Whoever compares, with a hygrometer, the atmospheric humidity inside and outside a low plant cover, is likewise struck by the high humidity which exists inside. Here also there is a two-fold cause. On one hand, the plant cover (even if dead) retards the removal of the water vapor given off by the soil, while on the other the living plant cover gives off water vapor continuously because it must transpire in order to live.

O. Stocker (*563*), for example, observed the following atmospheric humidity values in a meadow at Freiburg. These measurements were made on an almost calm day — July 18, 1920 — with an air temperature of 29°.

At a height of 100 cm in open air	57%
At a height of 13 cm, between clover leaves	78%
At a height of 2 cm, in the grass	96%

The extraordinarily high humidity gradient within the first meter from the ground appears clearly in these figures. On July 1–6, 1930, at Farmsen near Hamburg, E. Martini and E. Teubner (*702*) determined the following values of relative humidity in grass, on humus-filled sandy loam: —

TABLE 44

Hour of day	9 A.M.	12 Noon	3 P.M.	6 P.M.
In open air	88	56	48	78
In grass 50 cm high	89	68	49	80
In grass 20 cm high	98	85	78	80
In grass 10 cm high	98	90	88	88

The comparison between heat and water content does not hold absolutely, however. The temperature stratification reverses during the course of the day: the ground which gives heat to the air by day, receives it back by night. But as to humidity, the stratification, as a whole, remains constant; a considerable current of water vapor is continuously passing upward from the ground.

Nevertheless, as we look at it more closely, the humidity stratification in a low plant cover becomes really complicated at least when we are considering *relative* humidity, as is usually the case. It depends, of course, not only on water-vapor content but also on temperature. Let us first clarify the process of water-vapor enrichment in the plant-filled air layer near the ground.

The sum of all the transpiring ground and plant surfaces standing on a square meter of land amounts to between 20 and 40 sq m. The output of water is greater in proportion since according to the most recent research of P. Filzer (556) it is proportional to the density of the crop. One might at first think that the contrary restriction of evaporation and the screening of the ground which also increases with crop density would soon set a limit to the possible yield of water. Yet such limitation is not noticeable with even a forty-fold multiplication of evaporating surface.

According to measurements which J. Bartels and W. Friedrich (355, 357) made at the Eberswald lysimeter installation, evaporation from ground covered with vegetation is about twice that from bare ground. This value which applies to dry sod may, according to the studies of P. Filzer, increase to five-fold for other vegetation and — for a short time only — to a maximum of eight-fold. This plentiful supply of water vapor is more easily retained within the plant cover, the denser the latter is. Consequently the relative humidity mounts in proportion to crop density. For example, P. Filzer (556), as the average of several readings, obtained the following values in corn plantings of three different densities: —

TABLE 45

Density of stand	Dense	Medium	Light	Outside
Sq cm leaf area per cc air space	1.81	0.82	0.38	0
Relative humidity	73	64	51	41%

At the crop surface the hygrometer is very erratic as moist air parcels from the crop mingle with dry air from without.

If the ground is dry and the leaf development at a certain height

above it is especially rank, this will be evident in humidity stratification. On three different days in the summer 1907 Gregor Kraus (*12*) observed the following air humidities at a beautifully developed male fern which was growing in the shade: —

TABLE 46

	Forenoon	Noon	Afternoon
At 1 m (above the fern)	86	58	71
Between the leaves	95	70	88
On the shaded forest floor	88	60	72

The lack of evaporating leaves at the ground and probably also the reduced amount of evaporation of the soil at lower temperature make themselves felt.

To be sure the air between the leaves never attains complete saturation with water vapor. The amount of evaporation depends on the temperature of the evaporating surface, not on that of the air. As soon as evaporation begins, the evaporating surface experiences a cooling effect; this, in turn, reduces evaporation, so that the water vapor given off from the leaf surfaces does not suffice for complete saturation of the contiguous air. Consequently the air between plants also remains in general below 100%. R. Wenger (565) observed 98% between leafy plants on a rainy day. This is the highest verified value which has been observed. (It is recognized that determination of relative humidity close to the saturation point is attended with great difficulties.)

In dry times and dry regions (and here again in light plantings) the increase of air humidity between plants in comparison with the surrounding air is no longer noticeable since then the temperature effect prevails. O. Stocker (564), as a result of his studies of water balance of Egyptian desert plants, came to the conclusion that: — "There is no case where a rise of relative humidity within the leafy framework of a desert plant has been proved; on the contrary, in several instances the humidity in the neighborhood of transpiring leaves has shown a diminution. This phenomenon results from the fact that, on the one hand, the desert wind hinders any enrichment of the transpired water vapor about the transpiring organs, while, on the other hand, the insolation reflected from the earth and also from the plants as heat, favors an increase of temperature and a consequent lowering of relative humidity in proximity to the plants."

This temperature effect tends finally to the air in the lower plant cover being drier than that in the open. The measurements of F. Firbas (557) on habitat conditions over sandstone and basalt led to the conclusion that: — "Where the ground in open plant communities can warm up considerably above the air temperature, the relative humidity during the day decreases toward the ground. Where, on account of a close plant cover, the differences between air and ground temperature become less, or the latter lags behind the former, the opposite condition prevails, the relative humidity increasing toward the ground."

Returning to the manner of expression employed in Chapter 10, we may say: "Although the transfer of water vapor in the ground air is intensified through the plant cover, the vertical distribution of relative humidity is as a rule of the wet type. In dry regions and dry times the humidity stratification may reverse itself under the over-ruling effect of high temperature."

We have only one series of observations from the tropics — that of L. A. Ramdas, R. J. Kalamkar and K. M. Gadre (542). The results are shown in Fig. 137 and 138. They refer to the same research area at Poona and the same period from the 16th through the 31st of December, 1932 as does Fig. 136. In southern India a different humidity stratification in part was found over bare ground from that prevailing in Europe (see Chapter 10). Consequently it is impossible to say to just what extent the relationships indicated in Figs. 137 and 138 hold true for us. They do, however, give a good idea of water-vapor conditions in crops where they were noted.

Let us begin with relationships at the time of incoming radiation. The vapor pressure (Fig. 137) increases a bit toward the ground (wet type). In the unwatered millet field, the vapor pressure is about 1 mm higher on account of evaporation from the plants, but the stratification is the same as in the open. In the sugar cane, which must be irrigated from time to time, the vapor pressure at the wet ground is very high and decreases greatly with height. This is also true of the relative humidity in the sugar cane throughout the day (Fig. 138) for it decreases from 60% at the ground to 30% at a height of 2 m. In the open, on the contrary, there exists a weak form of the dry type of relative humidity in the middle of the day. Here too the millet field is intermediate between sugar cane and the open.

At night the dry type of humidity prevails for both degrees of moisture, since the black "cotton" soil of India has the property of absorbing a great amount of water vapor at night. A single exception exists in the irrigated field of sugar-cane (Fig. 137) where the

vapor pressure at night is higher in the first few centimeters above the ground than it is higher up.

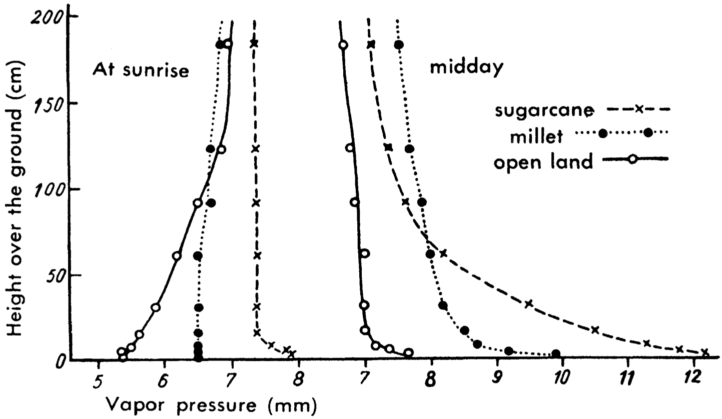

FIG. 137. Distribution of vapor pressure in the lower plant levels and in the open in Poona. (After L. A. Ramdas, R. J. Kalamkar, and K. M. Gadre)

Dew is of great importance in the water economy of plants, both at times of drought and in places which are prevailingly dry. Dew

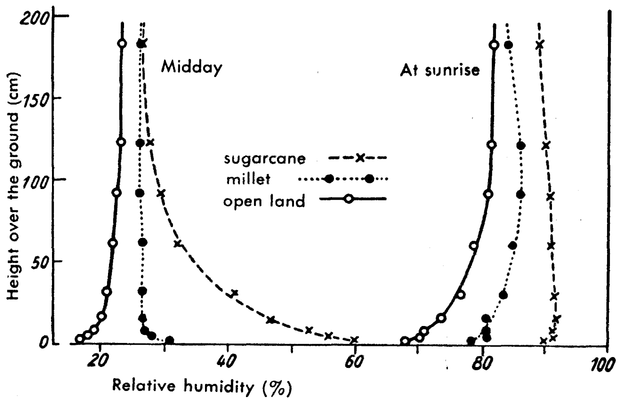

FIG. 138. Distribution of relative humidity in lower plant layers and in the open in Poona

is a form of precipitation whose frequency is dependent (as are frost and glaze formation) on the temperature of the wetted surface. Consequently dew is a microclimatic phenomenon. The dew-plate

developed and introduced to meteorology by E. Leick (*575*) today makes possible very comparable dew measurements in various localities. The more important publications dealing with dew problems are listed in the references pertaining to the preceding chapter [(*566*) to (*586*)]. Attention is called particularly to the summarizing report of J. Stephan (*580*).

Let us now turn to the effect of plant cover on wind movement near the ground.

The high daytime temperatures and the high humidity which we have described can exist amongst plants only because it is difficult for the wind which sweeps over the ground to penetrate the plant cover. Convection is noticeable in its upper portion only. The wind therefore merely "wipes away the vapor cap over the crop," as P. Filzer (*555*) so strikingly expresses it.

The movement of plants is such that their braking action is different from that of the solid ground. Leaves of different plants have different movements. Stalks of grain wave in the wind. Their sway is similar to oscillations of a mechanical system represented by the plant. The mass distribution in a tree determines the period of its movement to and fro once the impulse has been imparted by the wind. This is easily observed in a forest. If successive gusts in a storm accidentally strike a tree in rhythm with its natural period of oscillation, the danger of breakage or uprooting is much increased, as noted by A. Schmauss (*562*). Wind damage therefore need not result from wind pressure alone but may also result from this resonance phenomenon.

In 1915, G. Hellmann (*216*) in discussing wind research at Nauen, stated that an anemometer placed at a height of 2 m lost velocity if the grass beneath it was full grown. The growing grass had the effect of bringing the ground closer to the anemometer. In its braking action on wind velocity in the air near the ground the surface of the ground was no longer effective at height $z = 0$, but at another hypothetical surface at the height $z = z_0$. The value z_0 evidently depends on height and the kind of plant cover; it is called the "roughness height," z_0.

Calm prevails within the plant cover. Suppose one lies down on the storm-swept heath between bushes of calluna. "It seems as though one had dropped into a sink-hole: above, the elements battle — but under the callunas hardly a breath is felt" (A. Koelsch). These conditions have been numerically expressed in the excellent measurements of O. Stocker (*563*).

On the heath near Bremerhaven, for example, on Jan. 11, 1921, he observed the following wind velocities during a storm: —

At a height of 180 cm above the heath	9.3 m per sec.
Between the top calluna branches at 50 cm	3.7 " " "
Between the top calluna branches at 30 cm	1.4 " " "
Between the callunas at 10 cm	1.0 " " "

On the sunny, windy 12th of October, 1920: —

At 180 cm above the heath	5.1 m per sec.
At 40 cm — between the calluna tops	1.7 " " "
At 2 cm, in a small open space between the callunas — less than	0.008 " " "

On the basis of numerous similar measurements, O. Stocker (*564*) concluded that most German weedy plants are never subjected to velocities in excess of 1 m per sec — their normal amount being, on the contrary, often under 0.1 m per sec. The first example given above (3.7 m per sec between the calluna tops) represents the maximum which Stocker has ever measured. In a desert climate with strong winds, conditions are different. It need hardly be said that this wind protection, afforded by the plants themselves within the vegetation cover, is of great importance for their water economy.

W. Kreutz (*560*) by means of measurements at a height of 25 cm in a wheat field and in two other fields planted with beans and potatoes, respectively, has determined the braking effect of the plant cover on winds within it in percentage of the wind velocity. Summarizing his data, we find the following percentages: —

TABLE 47

Wind Speed (m per sec)	Braking effect in %		
	Wheat	Beans	Potatoes
Under 1	24	20	30
1–2	15	23	24
2–3	11	15	23
Over 3	9	11	..

Accordingly, the retarding effect of a low plant cover is relatively less, the higher the wind velocity. (We shall see in Chapt. 35 that it is just the opposite with the screening effect of a spruce windbreak.)

We now have a good series of measurements covering the in-

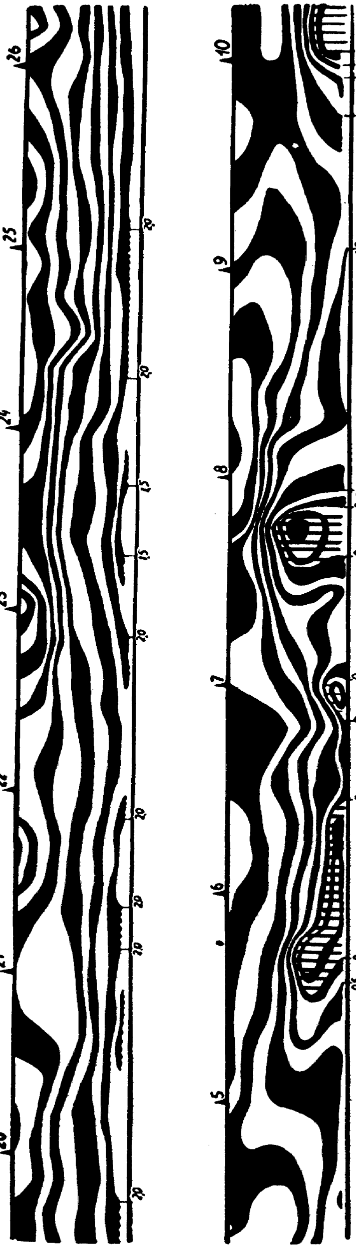

Fig 139. The different wind structure over a field of stubble (above) and a turnip field (below). (Taken from Wilh. Schmidt)

fluence of the kind of plant cover on wind retardation. In the first place let us consider Fig. 139, which represents the variation in wind structure over different kinds of fields. The method which Wilh. Schmidt (*112*) used in obtaining these measurements has already been described in Chapter 4. The scene of the observations was at

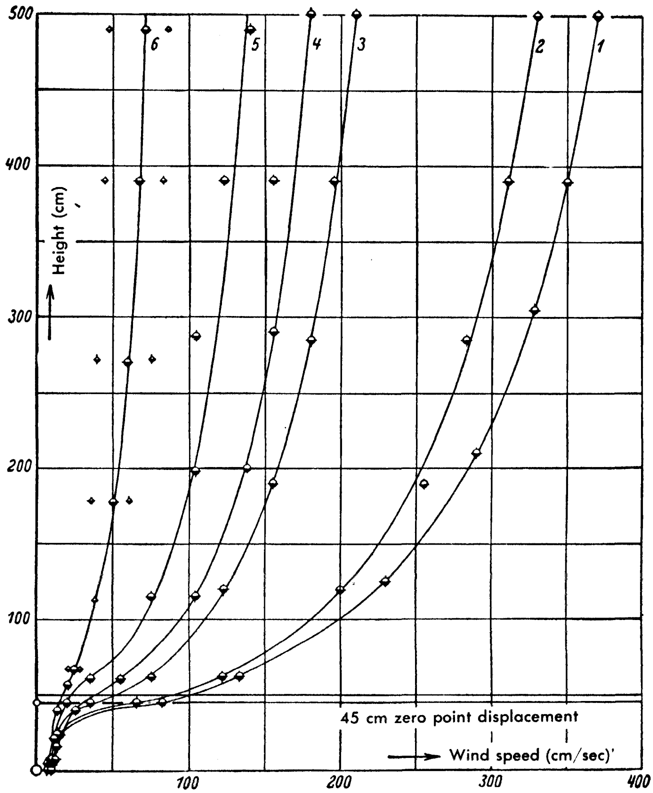

FIG. 140. Change in wind speed with altitude over a turnip field. (After W. Paeschke)

Hommelsheim in the Rhine valley, near Düren. Wire racks (wind-pressure plates) covered with cloth were placed over a perfectly flat field of wheat stubble. They were spaced 50 cm apart vertically and 60 cm horizontally. A similar installation was prepared over a turnip field whose uniformly dense growth of leaves lay from 40 to 50 cm above the ground. The wind had a sweep of at least 200 m across the turnip field before reaching the point of measurement. In

the case of the stubble field, the approach was much longer yet. In both instances the wind had time to adjust itself to roughness of the ground.

Fig. 139 represents vertical sections reaching to a height of $1\frac{1}{2}$ m above the stubble field or the top of the turnip leaves. The lines of

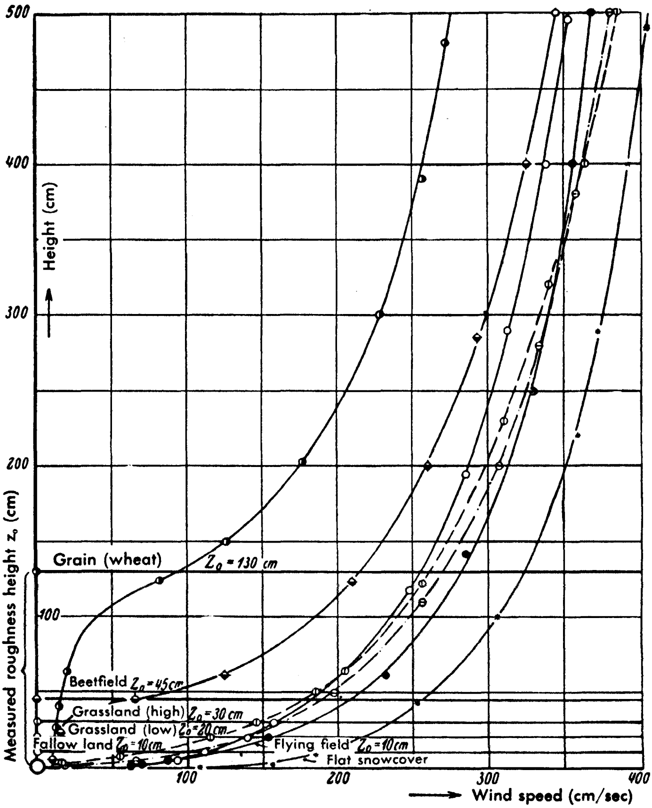

FIG. 141. Average wind velocity profiles over different types of plant cover and ground surfaces. (After W. Paeschke)

equal wind velocity are drawn for steps of 25 cm per sec, with the intervening spaces colored alternately black and white. Where the wind turns for a time into another than the prevailing direction, the fact is indicated by wide vertical shading. Both tests, as can be seen by the time scale, lasted only 5 or 6 seconds.

There is in general a normal wind stratification over the stubble

field and a uniform quiet circulation with a slight variation of speed with time. Above the turnip field, however, there is great turbulence. The rough, coarse surface at times even causes a reversal of the wind close above the leaves; at times the air seems to stand still (say for 5 seconds or so).

W. Paeschke (*561, 224*) carried out at Göttingen an experimental study of roughness, using the most modern research methods. In Fig. 140 we reproduce a representation of the windspeed distribution over a turnip field. Curves 1 to 6 correspond to tests at different hours on a clear radiation day. (July 26, 1935). As we leave the ground the wind speed at first changes only slightly. Only when we get above the crop surface does it increase — rapidly at first, then more slowly. The wind distribution with height can also be considered to apply here, if, instead of the ground surface, a roughness height z_0 equal to 45 cm is taken, and only from there up does the formerly given equation apply.

Naturally, z_0 depends entirely on the height and kind of the plant cover. Fig. 141 Paeschke's summary of measurements on different kinds of fields, even a bracken heath, an airport and a snow-field. For each type of surface, the roughness height is drawn in as a horizontal line. The wind distribution over the snow-field with its slight roughness is the same as that over the bare ground. In the other curves a two-fold division is necessary — the part below z_0 and the normal part above z_0. But it is not only the magnitude z_0 which depends on the height and kind of plant cover, but also the exponent a in the equation in Chapter 11, which represents the variation of wind speed with height. The measurements of W. Paeschke (*224*) gave: —

TABLE 48

Kind of Soil or of plant cover	Roughness height z_0 cm.	Reciprocal Exponent Value $1/a$
Smooth snow surface	3	5.0
Göttingen airport	10	4.3
Bracken	10	4.0
Low grassland	20	3.8
High grassland	30	3.6
Turnip field	45	3.0
Wheatfield	130	3.5

These results give us a complete picture of wind relationships within a low plant cover. In the forest the "roughness height" in-

creases to quite different magnitudes. The part below z_0 belongs to the calm trunk space, which we shall discuss in Chapter 32.

Besides the single factors thus far mentioned (radiation, temperature, humidity and wind) it is also useful at times to consider cooling, which depends on the other four. A. Kestermann (559) was the first to make comparative measurements of garden trees and shrubs, using two Pfleiderer and Büttner frigorigraphs. They showed the frigorigraph peculiarly suited to microclimatic research. We refer here to his easily accessible work.

CHAPTER 29

Forest Meteorology, Forest Climatology, and Stand Climate

From the low plant cover we proceed to the forest. To a certain extent this means passing from agricultural questions to those of forestry.

The term forest-meteorology includes all that unites the forester and the meteorologist. As meteorology is divided into climate and weather so also does forest meteorology include two rather different domains. The forester is interested in weather science insofar as the various weather processes are of significance for his forest. These are, in most cases, sources of damage — wind, avalanches, sleet, late frosts, droughts and such.

In forest climatology, macroclimatic problems should be mentioned first. A planting grows up in an alternation of favorable and unfavorable years. The forest manager consequently consults the climatic data of meteorological stations when he wants to determine the connection between weather cycles and growth. There is no forest development without a climatological basis. It is impossible to select kinds of wood and strains for development without a knowledge of the macroclimate, especially when it is a question of varieties native to other lands and climatic zones. The great work of C. A. Schenck (*615*) on foreign forest and park trees consists, in its first volume, of a macroclimatology of the various forest belts of the earth. In the long history of forest development it is necessary to make allowance for climatic fluctuations and changes.

The microclimate is of prime importance for the forester because it is the habitat climate of the young forest seedlings. The forest is never more sensitive to climate than in its formative years. The habitat climate of the plantation is, however, influenced by the cultivation measures employed by the manager. Consequently he has a direct, practical interest in the habitat climate. What has been said in the first chapters of Section VI as to the relation between the low plant cover and the microclimate applies also to the fundamentals of forest-meteorology as a science.

Beyond this the forester must be familiar with climatic relations in his older plantings. For one thing he will want to know how the forest responds to weather events; how the heat economy and the

water economy of the forest are maintained in the unity of crown-space, trunk-space and soil; how these relationships vary with the season, the type of wood, the age of the planting and its condition. Then the effect of this climate on the immediate surroundings of the forest will interest him, for he prefers to start his new plantations in proximity to the old and thus under the climatic influence of the latter. The microclimate in the neighborhood of a mature woods is therefore a habitat climate for the young growth. All these questions are treated in the following chapters. One might think they could be combined under the title, "forest climate," but that designation has come to have a different meaning in the course of the history of meteorological research.

When in the beginning of the 19th century the leaders of the French revolution most recklessly wasted the forest of France, the consequences soon appeared with frightful clearness. The European public almost as a unit became interested in the necessity of forest maintenance. Climatologists were given the task of determining the effect of forests on the macroclimate, its "welfare effect" as it was called, thus giving forest politics a powerful weapon. Various methods of attaining the goal were tried.

In the second half of the 19th century the newly established meteorological networks published their first series of measurements. They were first used and tested on the question of whether in heavily forested countries or sections the climatic relations could be proved different from those in unforested areas. In this direction, for example, H. E. Hamberg (*602*) and A. Woeikof (*635*) proceeded. With such a loose network of observing stations as existed at that time the method was inevitably unsuccessful. Latitude, altitude, continentality, topography, location with respect to centers of action in the atmosphere, and many other factors prevented the forest influence from being segregated. Soon the idea was suggested that the sudden deforestation or sudden reforestation of a country would set the scene for a magnificent experiment to this end. In the course of the varied history of mankind such cases have occurred. But there are other obstacles. In a country which neglects its forests the conditions are scarcely favorable for undertaking through careful scientific research to determine the harmful consequences of such wastefulness. Moreover, reforestation takes too long.

An exception to this is found in tropical lands where forest growth is amazingly rapid. In 1875 a new forestry law initiated a great reforestation project in the central part of southern India. In an investigation covering the decade before and after the reforestation,

H. F. Blanford (587) believed that he established an increase of precipitation as a result. A. Kaminsky (*606*) showed, however, that there had been a great climatic fluctuation in progress, by which the control stations chosen by Blanford outside the forest had, accidentally, not been affected. This is another proof of how difficult are such experiments with a widely-spaced network of observation stations.

In order to demonstrate the influence of forests on precipitation, J. Schubert (*629*) used — not the national meteorological network — but a supplementary network of 28 rain stations which were in operation for a decade in the forest region of the Letzlinger heath. In a careful analysis of the resulting observations, he separated the effects of altitude, latitude and the situation in relation to the sea. With such a close network this is possible. Moreover, he made allowance for the wind error in openly situated rain-gauges, and for the condensation of moist air. Then he was able to show, by calculating the probable errors, that the relationship between precipitation and reforestation was closer than the influence of all the other accidentally effective circumstances. The conclusion of this work which appeared in 1937 was twofold: —
1. Of the year's precipitation on the Letzlinger heath, 6% can be ascribed to the influence of reforestation, and 2. The influence of the forest in dry years is demonstrably greater than in the wet years.

In this connection, the first extensive observations are interesting which we have now-a-days from the tropic virgin forest, namely the Congo region. In 1934, M. Gusinde has made these measurements on the Ituri, a tributary of the Congo; F. Lauscher fully worked up these observations (*600b*). The yearly annual rainfall was remarkably greater in the clearings within the virgin forest than at the stations outside of the huge forest region. In 1934, on the Ituri an annual precipitation of 1979 mm was measured; for eight surrounding stations in N, E, S, and W amounts between 1127 and 1853 mm, on the average 1491 mm were found. Thus, the region of the virgin forest received 30 per cent more precipitation. In accordance with this fact, the relative humidity in the virgin forest was 15 per cent higher, the temperature of the air 1.5°C lower than in the surroundings. Although these values ought to be considered with great caution because of the short time of observation, the big area and the possibility of local influences (Hole-cuttings! see page 350) the observations speak more *for* an increase of rainfall by the forest than against it.

The classic method which was, in the 19th century, prescribed for determining forest influence on climate, consisted in the erection of so-called "duplicate forest stations," which were begun in Bavaria by E. Ebermayer (*592*), in Prussia by A. Müttrich (*611*, *613*) and were, in their general features, carried out in Austria too by von Lorenz-Liburnau—being imitated in many other countries. Meteorological stations were operated in pairs with one station in open country to study the open country climate and the other in a nearby forest to study forest climate.

It is evident that "forest climate" was considered to be the same as "trunk-space climate." But this is only one portion of forest

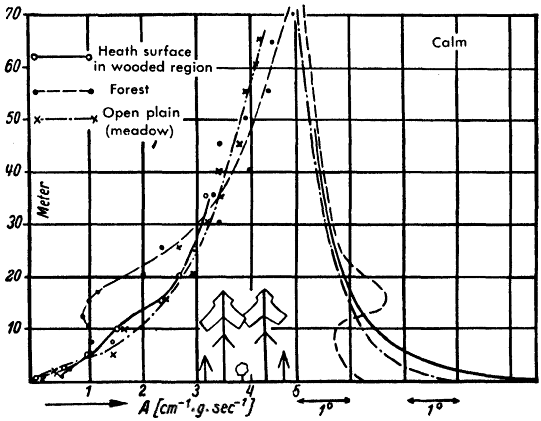

FIG. 142. Magnitude of Austausch (left) and temperature distribution (right) in open country and in the woods on a summer day. (After H. G. Koch)

climate. That it was the first to be noticed and observed is easy to understand, because a man walking through the forest experiences the physical and psychical effects of this climate first. Physically considered, however, it is a very unimportant part. A glance at Fig. 142 will show this at once.

H. G. Koch (*133*), by attaching electric resistance thermometers to small rubber balloons, was able to measure temperature and convection in the first 100 m above the ground. He also included in his measurements a 17 m pine forest in the Lüneburg heath. At 11 A.M. on August 28, 1936 the temperature distribution in the forest and in the neighboring open country was that shown at the right in Fig. 142. The incoming type of radiation was well developed above the open country. On a heath area surrounded by forest the tem-

peratures near the ground were still higher, as a result of the lesser convection there. The type of temperature profile remained the same. It was very different in the forest. In the space above the sunny crown the air is really warmer than at the same height in the open, but what is gained there is lost in the trunk space. Fig. 142 makes it clear that no conclusion as to the effect of the forest on the macroclimate can be drawn from a comparison between open country climate and trunk-space climate near the ground. Such a conclusion requires consideration of the whole atmosphere affected by the forest.

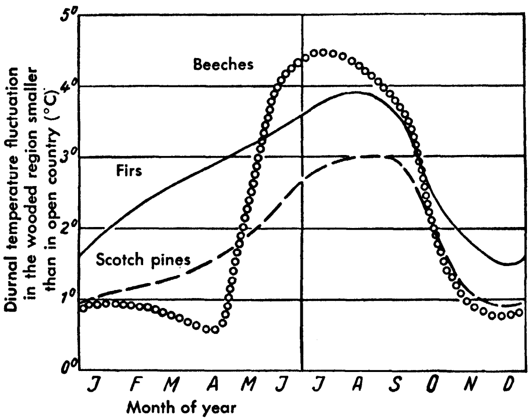

FIG. 143. Influence on the kind of forest on the diminution of diurnal temperature fluctuation in the trunk space in comparison with open country. (After A. Müttrich)

If one is aware of these hypotheses, he can proceed on "forest climate" research of his own with undivided interest for they afford an excellent insight into the *trunk-space* climate (as it is experienced by a man walking through the woods) in contrast to that in the open. The data of duplicate forest stations have been thoroughly edited by H. Burger (*589, 590*), von Lorenz-Liburnau (*608*), A. Müttrich (*611–613*) and particularly, by J. Schubert (*617–629*). Here we shall briefly describe the air temperatures.

The effect of shading by the forest crown is to reduce the temperature range in the trunk-space in comparison with that in the open. The amount of difference depends to a high degree on the kind of tree. Fig. 143 shows the small daily temperature fluctuation in the trunk-space as compared with the open according to a 15-year series

of observations made by A. Müttrich (*611*) at 5 pairs of stations in a fir forest, 4 in a pine forest and 6 in a beech forest. The observations were made outside and inside a shelter placed 1.8 m above the ground.

All three curves show the anticipated annual march with a maximum in summer when radiation is strongest and a minimum in early winter. Most striking is the curve of the deciduous forest. When, in spring, the increasing insolation falls on the bare beech forest, the difference between field and forest is slight. What the trunk-space loses to the open in radiant heat on account of the shade by trunks and branches, it regains because its quiet air retains the heat. Reference has been made previously to the unusually high temperatures which F. Firbas (*288*) found about this time in the leaf mold. As soon as the leaves come out there is a sudden change. The dense leafy crown intercepts all radiation. The daily fluctuation in the beech forest is reduced almost 5° on the average and reaches a value which is attained by no other kind of wood at any time.

The evergreen forest is much more uniform in its range. The trunk-space is at no time shielded so little as is the deciduous forest before the leaves come out, nor so much as is the beech forest in full leaf. The curves for the two kinds of evergreens run practically parallel. That of the spruce forest, with its dense, dark crown, is at all times somewhat higher than that of the lighter pine forest.

If a person wishes to tackle the problem in general of the influence of forests on the macroclimate it can be done only by first investigating the heat and water balance of the forest in its entirety and comparing the result with the heat and water balance of unplanted ground. In so doing he does not measure the effect but goes back to the causes on which it is based.

Even those interested chiefly in the practical side of forestry are eager to understand the forest itself as a meteorological whole. Since, on grounds earlier mentioned, the word "forest-climate" must be avoided, we shall by preference speak of a "stand" climate. The term stand climate consequently is to be understood as including the microclimate of the crown space together with its sphere of influence, the trunk-space climate (which Boos (*657*) has well called the "climate inside the stand", the climate of the forest floor and the climate of the air layer next to it insofar as the latter differs from the trunk-space climate.

As Fig. 142 indicates, the stand climate as a whole can be understood only by fixing the attention mainly on the outer active surface

(Chapter 27). This — in the stand — is the crown surface. There is where the measuring instruments must be placed, for there is

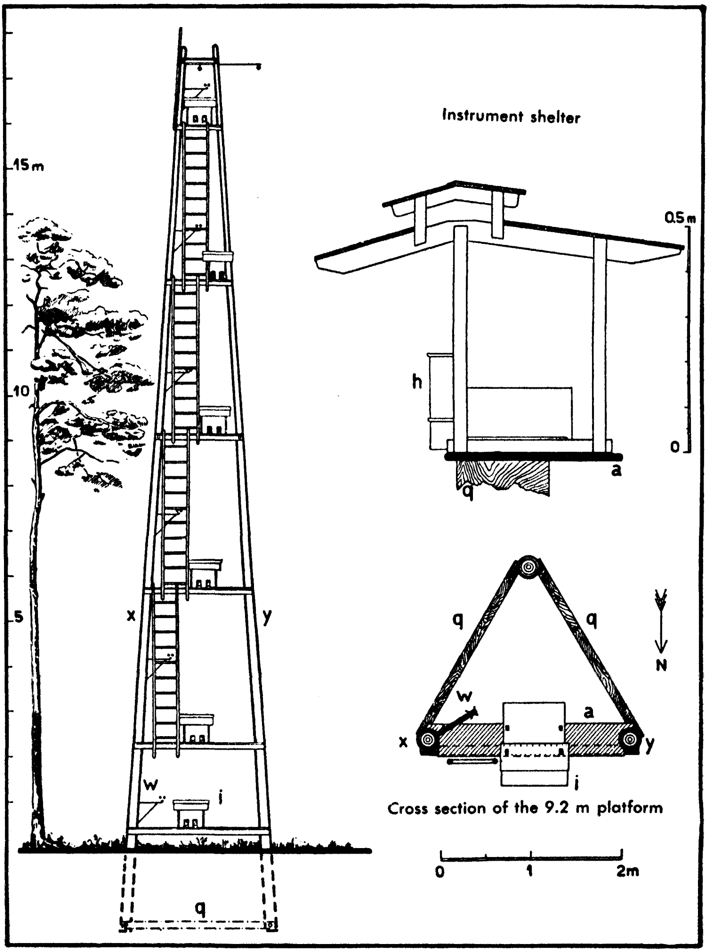

FIG. 144. Observation scaffold at the Wondreb Forest station for the investigation of forest climate. (After R. Geiger)

where the meteorological processes take place. Latest research has proceeded along this line.

In 1924, the Forest-Meteorology Institute of Munich, under the direction of A. Schmauss, first erected a strong, high observation

tower in a pine plantation in Ostmark, Bavaria. To illustrate the method of work, the scaffold is represented in Fig. 144, as R. Geiger (*649*) described it. It was built like a hunter's look-out, on a triangular plan, using three tree-trunks (*x*, *y*), to which six platforms for instruments were attached, and which were united at the top by cross beams (*q*). In order to protect the instruments as much as possible from any influence due to their installation, the six stories were not built solid, but protecting roofs (*i*) were erected over a transverse board so as to protect against rain and hail. Otherwise, the air had free access to the instruments. Beneath the protecting roof there was a thermograph, a hygrograph (shown at *h* in Fig. 144 so as to indicate the general lay-out), and the attendant control instruments. The anemometers (*w*) were mounted between the floors in order to avoid interference by them; iron brackets held them at the proper distance from the poles. Access to the instruments for the observer who was in constant attendance during the time of measurement was by means of a ladder on the outside of the tower, beside which ran the electric wiring for the anemometer, whose indications were recorded in a forest hut.

This method of investigation has been used many times since. In 1927 R. Geiger and H. Amann (*650*) built two 27 m scaffolds of a similar sort in an old oak wood of the Schweinfurt Forestry Department. About the same time C. Schmid-Curtius (258) erected a very solid tower in a 20 m fir planting at Inselberg in Thuringia, which was used principally in studying the health-giving effect of the forest. Finally in 1931 H. Ungeheuer (*654*) built an observation platform equipped with electric thermometers in a 17 m beech wood in the Taunus. At the four places mentioned, which are situated in plantings of four different kinds of trees, research has been carried out on forest climate as a whole.

The meteorologist who has to watch and care for his instruments on a scaffold continuously, experiences at first hand how the crown space governs the forest climate. R. Geiger (599) has given us a description of it.

In the following chapters — 30 to 33 — this stand climate will first be described in a high, thrifty old planting, ready for cutting. We shall then indicate, as an example, how far the forest follows the processes of free air and how it differs from them, thus giving rise to a special climate. Chapters 33 and 36 will then take up the influence of stand composition, the microclimate of clearings and cuttings and that of stand borders.

CHAPTER 30

Radiation Relationships in an Old Stand

In connection with Fig. 127 we showed how the radiation of sun and sky on meadow is absorbed throughout a relatively large vertical range. In a forest too, the radiation is caught by leaves and needles, twigs and branches so that only a little is able to reach the forest floor. The "outer active surface" in the case of the forest is the crown surface. In contrast to the meadow, however, the greater part of the radiation is obstructed by this highest layer of the plant cover.

Fig. 145 shows the brightness distribution in a 120 to 150 year old stand of red beech intermixed with occasional spruces which was located on a 20° southeast slope at Lunz (Austria) about 1000 m above sea level. The measurements were carried out by E. Trapp (*646*) in 1937 by means of photocells, which are especially sensitive to yellow and green light, using an observing tower with several platforms. The data from sunny and cloudy days are averaged separately and shown thus.

In general about 80% of the incident radiation is caught in the crown space. Less than 5% reaches the forest floor. Although the absolute amount of radiation on sunny and cloudy days is naturally very different, the relative distribution shown in Fig. 145 indicates no difference worth mentioning. On sunny days the relative absorption is greater because the proportion of direct insolation is greater. But on cloudy days there is only diffuse sky light, which, because it is not uni-directional, penetrates the interior of the stand more easily. This applies particularly to the upper part of the trunk space. On the forest floor the difference doesn't amount to much.

A series of other measurements has proved that, for a definite place in the forest floor the relative amount of illumination received is fairly independent of the prevailing weather. A. Ångström and C. Chr. Wallén (*637*) ascribe great practical significance to this circumstance. It makes it possible, they say, to use the many years of radiation observations available at meteorological stations in the open for the determination of the radiation used by plants standing in forest shade. If one has completed only a short series of measurements at the place in question in any kind of weather, the conver-

sion factor is at hand by which the series of many years' length can be applied to the place desired.

Fig. 145 shows the distribution of illumination in a single stand. What fraction of the outside light penetrates in general to the forest floor depends to a great extent on the kind of woods, the age of the stand, its closeness and, in the case of deciduous trees, on the

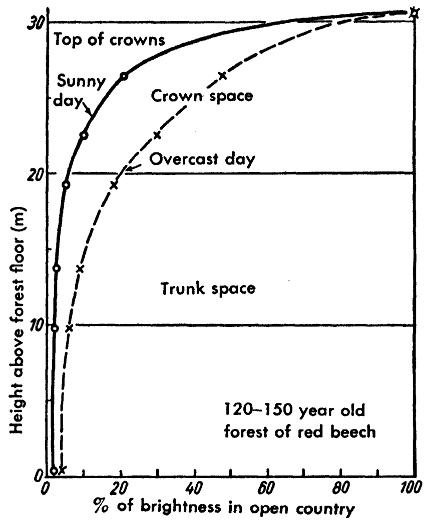

FIG. 145. Decrease of brightness in the interior of a thick foliage of red beech growth. (After E. Trapp)

stage of leaf development also. A man walking in the forest enjoys this dim, colored light. The difference between dark spruce forest and a light pine stand impresses one. But the habitat factor — *light on the forest floor* — is also of direct significance to its utilization by the undergrowth, by sprouting seedlings and the ground flora of the forest, in its growth.

J. Wiesner (*647*) was the first to undertake a systematic series of measurements, using Hecht's optical wedge. The optical wedge gives values for the wave length range between 360 and 440 mμ — the blue part of the spectrum. R. Geiger and H. Amann (*650*) carried out measurements by this same method during 1928 and 1929 in a 115 year old oak forest at Schweinfurt. More recently barrier layer photocells with different sensitivity have been used, in some cases with light filters. Experiments in many stands were made by F. Lauscher and W. Schwabl (*642*) in 1933 and by F.

Sauberer and E. Trapp (*644*) in 1935-36. The following table, arranged according to kinds of trees will give an idea of their findings: —

TABLE 49

Kind of Trees (old stand)	Illumination on the forest floor in % of outside illumination		Source
	Leafless	Leafed out	
	Deciduous		
Red Beech	26–66	2–40	*647, 642, 646*
Oak	43–69	3–35	*647, 650, 644*
Ash	39–80	8–60	*642*
Birch	...	20–30	*642*
	Evergreen		
Silver Fir	2–20		*640*
Spruce	4–40		*647, 642*
Scotch Pine	22–40		*642, 644*

The figures fluctuate decidedly with the composition of the stand. They show the general limits which — aside from extreme cases — have been actually observed.

The following numbers show by an example the variation of brightness in a stand of timber in dependence on the development of the vegetation and the character of the stand. The measurements were executed by W. Nägeli (*643a*) in Adlisberg near Zurich in 1939, in a 70 year old stand. The conifers (*A*) were pure firs. The mixed forest (*B*) consisted of 55 per cent firs, 36 per cent beeches, and 9 per cent other deciduous trees. The deciduous forest (*C*) comprised 73 per cent beeches, 22 per cent ash trees, and 5 per cent other deciduous trees.

TABLE 50

Time of Measurement:	Brightness in the stand in % of that above open land		
	Coniferous trees (*A*)	Mixed trees (*B*)	Deciduous trees (*C*)
End of April before sprouting	8	22	51
End of May after sprouting	7	14	23
End of September shortly before foliage changes color	4	4	5

With the deciduous trees the scattering of the individual values was much greater than with the conifers, especially in the time before sprouting.

An individual observation, a tropic virgin forest, 30 m high in the region of the Congo shows, according to M. Gusinde and F. Lauscher (*600b*), at 2 meters above the forest ground only 1 per cent of the outside brightness. Below 2 m the decrease of brightness was again considerably under the influence of the vegetation near the ground so that just at the ground we must expect about 0.1 per cent. This remaining light is entirely diffuse. H. Eidmann (*640a*) found in a mountain wood at Fernando Poo 0.4 per cent.

The values are in agreement with the observations which J. Deinhofer and F. Lauscher (*640*) made on the shortening of the duration of twilight in a forest. By "twilight" is meant the period between sundown and the onset of darkness (when reading is no longer possible in the open). In a deciduous forest the end of "civil twilight" occurs 16 minutes earlier than in the open; in an evergreen forest 20 minutes earlier, and in an old, high forest, 28 minutes earlier — assuming a cloudless sky. If the sky is cloudy the curtailment amounts to three quarters of an hour — in rainy weather, to as much as 54 minutes. These facts are recognized as significant in the settlement of cases at law.

It follows, as a result of the different permeability of deciduous leaves for various wavelength bands, of which we have spoken in Chapter 26, that the crown space acts not only to weaken, but also to filter, the radiation. For example F. Sauberer (*522*) observed in a 7 to 10 m stand of white beech in the Wienerwald one cloudy day in May between 9 and 12 A.M., that the orange radiation (at about 0.6 μ) was reduced to about 8% of its value in the open, yet the total radiation was reduced only to 20% of its original value, for, in the second case the wavelengths around 0.8 μ, where there is maximum permeability, were included also.

The filtering of light is very evident if attention is paid to the kind of radiation which is effective in the stand in spring when the leaves are coming out. K. Egle (*511*) found the following intensities of radiation expressed in percentage of radiation of equal wave lengths falling on the stand: —

TABLE 51

In the band of	0.71	0.65	0.57	0.52	0.45	0.36μ
Color	red	orange	yellow	green	blue	violet
March 12 (Buds still closed)	61	54	51	48	46	44
April 15	59	39	36	33	32	30
May 10	19	6	7	6	6	5
June 4	14	4	5	4	3	3

As the leafy roof thickens and the season advances the radiation is increasingly reduced but in the blue (short wave region much more than in the red).

G. Mitscherlich (*643*) has made many measurements of the dependence of light relationships on the age of the stand in numerous spruce plantings in the Dietzhausen forest district. This district is in the Frankish Buntsandstein region on the south watershed of the Thuringian forest. With a "Sixtus" photometer such as is used in photography as an exposure meter he observed in 87 different stands the illumination as compared with measurements in the open just before and after. The result is shown in Fig. 146.

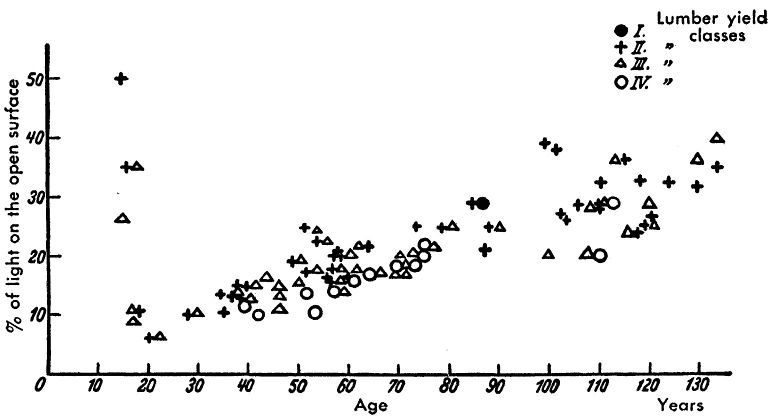

FIG. 146. Dependence of brightness in the interior of pine forests on the age of the growth. (After G. Mitscherlich)

The first young open stand closes in so that by the time it is 17 years old the dense crown allows scarcely 10% of the outside light to penetrate. But then as its age increases there is a steady increase of interior illumination. At the age of 120 years a value of 30 to 35% has been reached. The better yielding classes (I, II in Fig. 146) with their less numerous but more sturdy trunks let through in general more light than the poorer ones.

Comparative observations showed that these figures afford a practical habitat factor for the ground flora. With illumination below 16% the forest floor remains bare. Between 16 and 18% the first unpretentious mosses appear. Between 22 and 26% scattered berries are found and at about 30% the first spruce copses. These values naturally assume favorable soil conditions, otherwise the limits are higher.

Thus far we have spoken of average conditions in different stands. What about differences between very limited areas in one and the same stand?

One often notices, on a sunny day, how stray sunbeams break through the tree top canopy—how spots of light appear on the

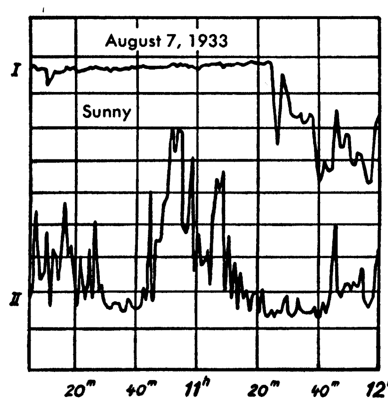

FIG. 147. Recording of the brightness on the outer half (I) and inner half (II) of an oak forest. (After F. Lauscher and W. Schwabl)

forest floor and move on with the course of the sun. At a given moment there may be the greatest differences in brightness between adjacent places. Or at a given place on the forest floor, there may be great fluctuations in brightness from one moment to the next. Fig. 147 is a reproduction of two records made by means of Lange photocells about midday on the sunny 7th of August, 1933. Curve I is the illumination on a meadow, influenced only by solar elevation and by cloudiness; Curve II is a similar record within a 40 year old ash stand, 16 m high. The two areas were close together, at Pressbaum, 25 km west of Vienna. The records were published by F. Lauscher and W. Schwabl (642). In addition to the weakening of

the light, they indicate the prevailing irregularity of the light factor at the forest floor.

This irregularity decreases as the sky becomes clouded and the ratio of direct to total radiation also decreases. E. Trapp (*646*) has determined the distribution of illumination throughout the greater

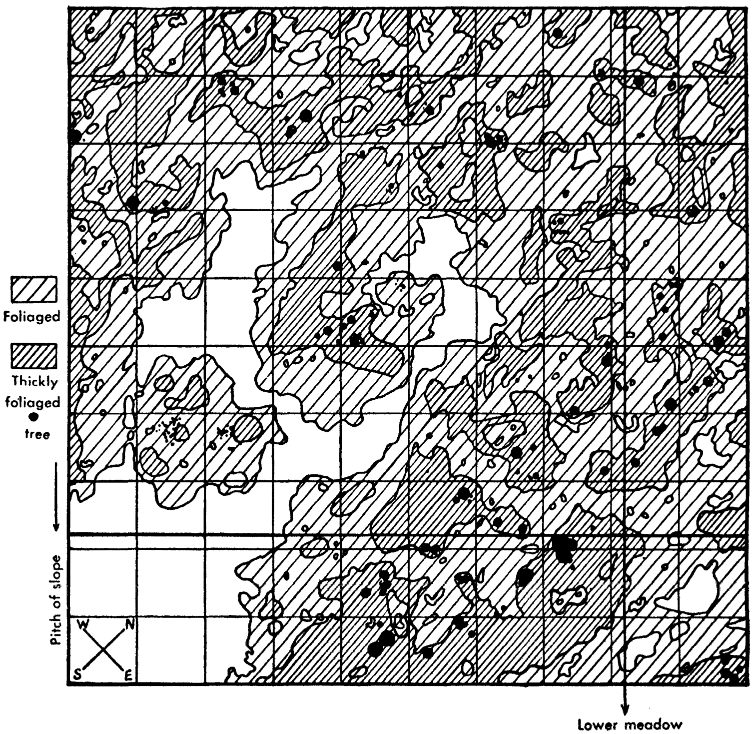

FIG. 148. Map of crown density of a 150 year old beech growth at Lunz. (After photograph by E. Trapp)

part of a stand by means of thousands of separate measurements and has depicted it on maps. We present, as a sample, one of his "cloudy weather illumination maps." Special significance is attached to these maps in that they coincide closely with vegetation maps.

Fig. 148 represents the amount of ground coverage by the crowns of a 150 year old beech forest covering 50 m sq, according to careful measurements: A meadow borders the stand at the lower left and extends two arms into the forest. Fig. 149 represents the accompany-

ing average distribution of illumination with a clouded sky. The brightest parts have more than 80% of the outside illumination; the darkest, less than 2%. The sky screening by the tree tops makes itself felt even over the meadow. The distribution on an occasional cloudy day is uniform compared with that in fair weather and shows no abrupt changes. Trees standing alone have no practical

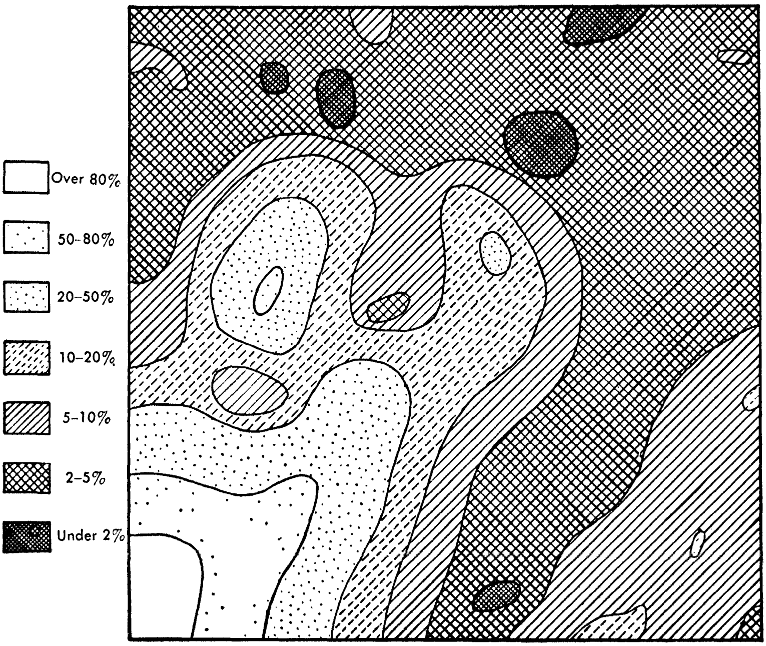

FIG. 149. Distribution of brightness in cloudy weather in the beech woods of Fig. 148.

effect on their surroundings, but groups of trees are very effective.

All illumination measurements within a stand which have been quoted hitherto, have dealt with quantities of light falling on a horizontal surface — the so-called "overhead light." K. Brocks (639) has also investigated the lighting of surfaces at various inclinations within a stand. His findings in an oak, a pine, and a beech stand may be consulted in the summary published by J. Schubert.

More simple than daytime radiation relationships, are those of the night. Outgoing radiation proceeds exclusively from the upper surface of the tree crowns. As P. Seltzer (653) observed in the

Hagenauer forest, leaves in the tops of the trees cooled off 2.5° below the temperature of the surrounding air, when the wind is calm and the sky half clouded, while leaves below the crowns cooled only about 0.4° below. The former radiated heat toward the night sky; the latter only toward the somewhat cooler tree crowns. Nocturnal cooling in an old stand, therefore, is entirely a function of the outer active surface.

CHAPTER 31

Temperature and Humidity Relationships in an Old Stand

The radiation relationships depicted determine in general the temperature relationships. First let us try to give a clear picture of the connection between the two. For this purpose, Fig. 150 and 151 will give us the daily temperature march in an old oak stand in the Schweinfurt forest district, according to the observations of R. Geiger and H. Amann (650). The stand was 24 m high; the 115 year old oaks were interspersed with 40 to 50 year old beech pole wood.

A series of thermocouples was erected on an observation scaffolding like that shown in Fig. 144, so that a temperature measurement could be taken at all levels of the stand — even above the crowns. The thermocouples could be connected in turn, by means of a rotary switch, with a Zeiss loop galvanometer standing on the ground. A temperature profile was obtained by measurements at seven points every 30 seconds. Off and on there were pauses for testing the instruments and making comparative readings. The figures give an excerpt from the record on the calm, sunny 18th of August, 1930. In order not to overcrowd the sketch the data from two stations in the crown space have been omitted. The lines indicating the other five stations are heavy in proportion to their closeness to the ground.

The cross-section of the thermocouple wires was so great that the temperatures shown are not true air temperatures but are affected by direct insolation. The amount of this influence cannot be given exactly, but it may be assumed that the thermo elements do not respond much differently from small twigs or leaves on the tree. Figs. 150 and 151 are therefore excellently suited to make clear the daily temperature march in a high old stand, in its response to nocturnal counter-radiation and, in particular, the continuous effective diurnal radiation from sun and sky.

The record (Fig. 150) begins at the time of sunrise. It is coldest in the oak crown (23 m) in agreement with the conditions of outgoing radiation as described in foregoing chapters. It is warmest on the forest floor. As the sun rises, warming-up sets in above the crown (27 m) as a result of the first level rays stretching out across the stand. It increases rapidly, so that after an hour the temperature there is about 5°C higher than in the whole stand, where uniform

temperatures prevail at nearly all levels for practically the whole night. Not until after 7 A.M. (see second line of Fig. 150) does the crown space, as the sun climbs higher, begin to warm up, while even yet it is still cool on the forest floor. This is the hour when the whole insect world arises in this favored warm and light zone of the forest.

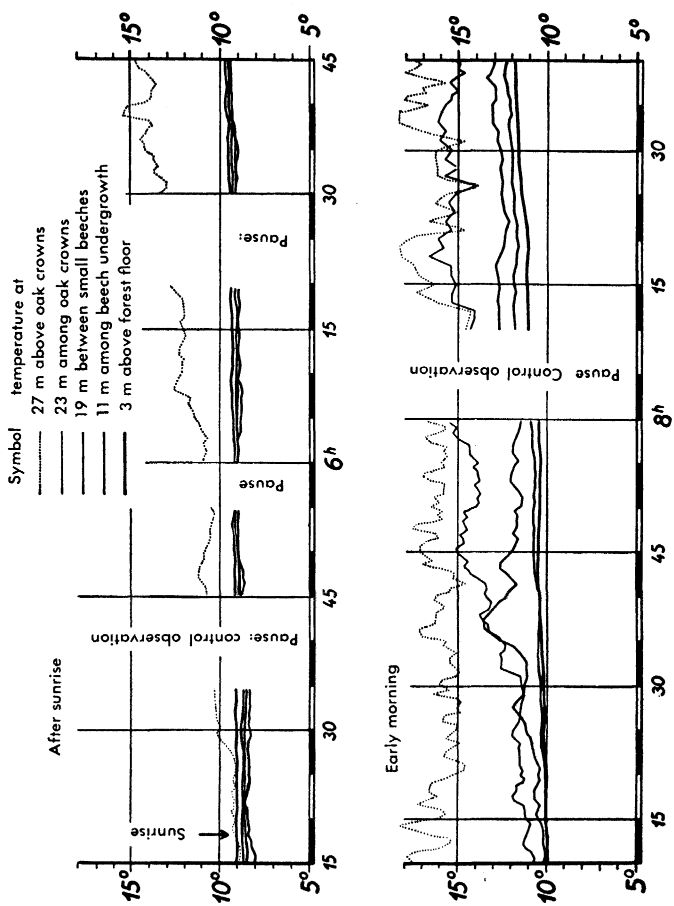

FIG. 150. Course of temperature at different heights in an oak forest on the morning of August 18, 1930. (After R. Geiger and H. Amann)

By 8:20 A.M. the temperature in the crown space (23 m) has equalled that above the crown, and as time goes on, surpasses it, for the dense crown canopy now absorbs the radiation of the higher-rising sun. Finally, now — three hours after sunrise! — the lower layers of the forest at last begin to share in the day's heat. (The

temperature lines at the lower right of Fig. 150 rise and draw apart.) But from above the cool outer air sinks into the stand. The strong heating of the crown canopy acts in conjunction with it to produce a vigorous temperature turbulence in the realm of the tree tops. There thus results about midday the condition represented in the

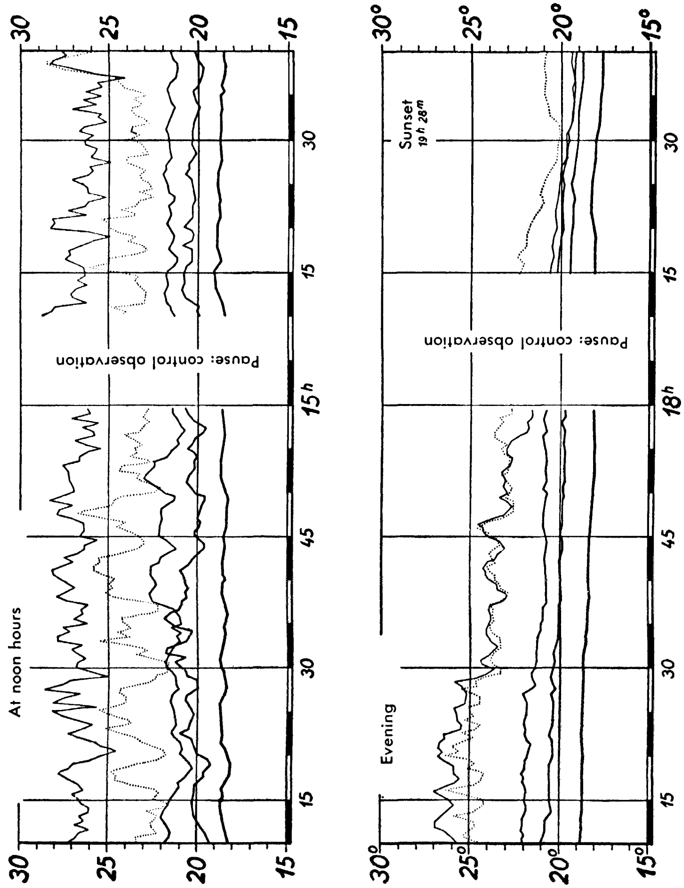

FIG. 151. Course of temperature at midday and in the evening in the same oak grove

upper half of Fig. 151:—In the crown space is the highest temperature and the most unsettled temperature condition. Above this in the free air, and below it in the trunk space, the temperature decreases; in the latter direction in particular the temperature disquiet decreases also. The lowest line, which corresponds to a height of

3 m above the forest floor, shows the amazing uniformity of temperature which the forest traveler finds so pleasant of a summer noontime — usually without thinking what a lively heat exchange is going on above him in the crown space.

Nevertheless the midday hours show a stable condition. The lines, with the exception of fortuitous fluctuations, run in a horizontal direction. This is the time when heat input and output are practically equal; the forenoon temperature rise is ended; the afternoon fall has not yet begun.

The reverse temperature movement in the second half of the day follows the same course as the morning rise. The example, which is taken from the period about 6 P.M. (in the lower part of Fig. 151) shows a smoother curve than that of the morning. The cause lies in the stable stratification of the cold air which is constantly sinking down from the crown space. The morning heating has to overcome the stability of the nocturnal temperature stratification; the evening cooling is furthered by the establishment of this stable stratification.

From the record as reproduced we see the normal temperature stratification in an old stand. By night, temperature differences are slight. Either the whole air mass is isothermal or, if the crown canopy is sufficiently dense, the cold air remains above it. This is the opinion expressed by von Lorenz-Liburnau (*608*). R. Geiger (*649*) once observed a temperature minimum in the crown of a pine stand. In connection with Fig. 153 we shall revert to similar results of H. Ungeheuer (*654*). But such differences can amount to only a few tenths of a degree. On the other hand it happens in light stands that the sinking cold air of the crown space results in a temperature minimum on the forest floor. P. Seltzer (*653*) observed a double minimum — one in the crown, the other on the ground.

While nevertheless such differences have more theoretical interest than practical significance, the temperature contrast during the day is very significant. Aloft in the crown space there is a very marked temperature maximum. This is, as one might guess from the evenly drawn recording, not simply a radiation effect, but may also be confirmed by measurements of the true air temperature. In thin stands a second weak maximum at the forest floor may sometimes be demonstrated.

At Leningrad, N. von Obolensky (652), in May and June 1922, determined the temperature distribution in a young growth of fir, using an Assmann aspiration psychrometer, and in July, August and September, did likewise in a young oak growth. As the mean of the 1 P.M. temperature on clear days he found: —

TABLE 52

Month	Forest floor	In the crown	Crown surface	At some distance above the crown
May	16.6	16.4	19.7	16.8
June	19.7	18.9	23.2	20.5
July	19.2	20.1	22.1	21.6
August	18.1	18.3	21.0	20.4
September	15.0	16.1	18.7	17.9

Here the temperature maximum lies at the outer active surface.

The average diurnal march of the air temperature in the stand is shown in Fig. 152. It is the mean of 12 calm September days of

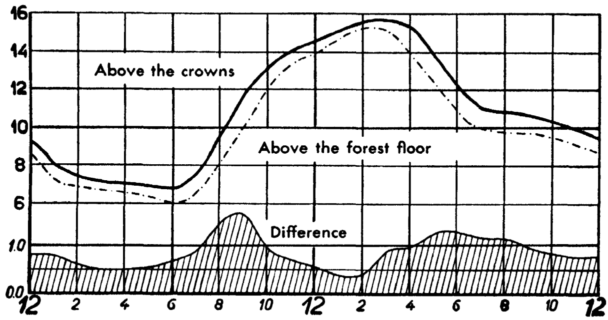

FIG. 152. Diurnal course of temperature in a pine grove in September 1924. (After R. Geiger)

1924, in a 14 to 16 m, 65 year old pine stand, as observed by R. Geiger (649). The solid curve refers to the record just above the crown (16 m); the dot and dash curve, to that 0.5 m above the ground. At the lower edge of the diagram the temperature difference is shown on an enlarged scale.

It is always warmer above the crown, but the difference at night is slight and uniform, when the regulation of temperature at the time of the nocturnal calm is exclusively from the tree crowns. There is, moreover, a minimum difference about noon, when the high sun penetrates at least partially into the forest, and when at the time of maximum wind velocity (which, as is well known, occurs around midday,) convection is most fully developed. The difference maxima, however, occur morning and evening, when the sun is low and convection slight.

In 1931 and 1932, H. Ungeheuer (654) made extensive records of true air temperature in a 17 m, 136 year old beech stand on the northwest slope of the Taunus. He placed resistance thermometers in small wood shelters protected from radiation. The data have been arranged according to average values for hours, months and years—also according to weather conditions. As an example, we give in Fig. 153 the daily march on clear calm summer days.

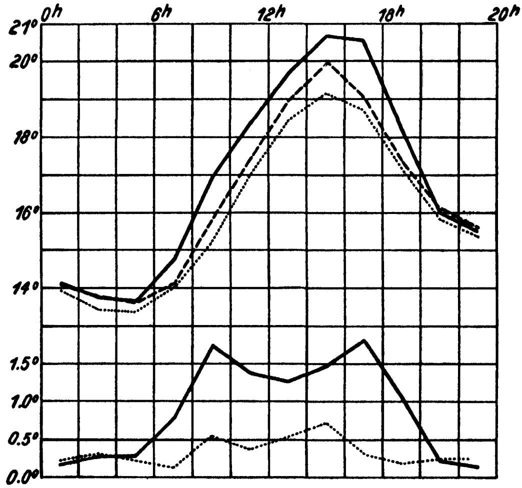

FIG. 153. Diurnal course of temperature in a beech grove on a bright summer day. (After H. Ungeheuer)

In the upper half of the diagram the temperature march in the crown space (at 17 m) is represented by a solid line; in the trunk space (at 11 m) by a broken line; and at 3 m above the ground by a dotted line. All the laws which have been described are illustrated. It is noteworthy how in the evening, the cooling effect of the outgoing radiation from the crown canopy appears in the difference between the solid and the dotted curves. The curve of differences between crown and ground shows the same double wave as Fig. 152.

The relative humidity in an old stand is governed principally by the water output of the leaves of the crown space. E. Ramann has demonstrated, as J. Schubert (627) reports, the great scarcity of water at about ½ m depth in the forest soil, that is, in the root region. The forest floor evaporates water to an extent dependent on the

degree of development of the ground flora and the openness of the stand. The lack of air movement in the trunk space retains the water vapor so that high humidity is the most characteristic feature of its microclimate. Drying out occurs only from the top, where the higher daytime temperature is favorable to a lower relative humidity.

The vertical distribution of relative humidity shows several types in the course of the day, which are represented in Fig. 154.

Before sunrise there is high humidity in all layers; when dew is precipitated, complete — or nearly complete — saturation. The observer on foot in a forest is not apt to notice much dew formation,

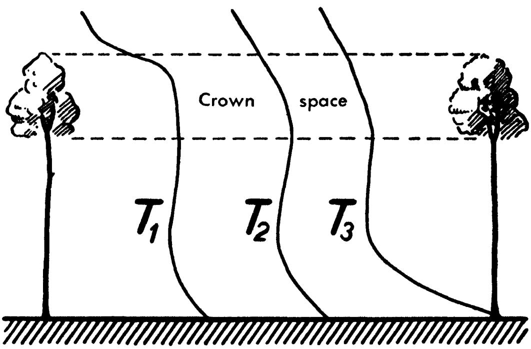

FIG. 154. Types of distribution of relative humidity in the grove

since in an old stand his attention is on the forest floor. Most of the dew, as I have several times been able to observe, is deposited on the upper surface of the crown, decreasing continuously and decidedly downward into the inside of the stand. Above the crown the deposition of dew was so great at times that it required several hours of sunshine to complete its evaporation.

As soon as the sun has risen, the warmed up crown surface begins to dry up. Through the action of the drier outside air on the upper part of the crown space, there results the distribution which is characteristic of the "morning type," as shown by curve T_1 in Fig. 154. — dry above, nocturnal moisture still evident below. The atmospheric boundary layer which we recognized in describing the morning temperature relationships at the top of the crown surface can also be easily recognized in the relative humidity by the course of the curve T_1.

As the sun gets high and the wind freshens normally, effecting a more thorough mixture of outside air and forest air, the drying out process penetrates the interior. The forest atmosphere now receives water vapor chiefly from two sides — from the forest floor and from the crown canopy with its countless transpiring leaves or needles.

So two surfaces appear in the stand climate in reference to the humidity. While the forest floor surface plays only a subordinate role in respect to temperature, it is very important for the transfer of water vapor. Although the temperature maximum at the forest floor, when there is one, is always slight, the *humidity* maximum is well developed, especially when the forest floor has a living plant cover. As proof of this we offer the measurements of O. Stoker (*563*) which he made within a high spruce forest on the Riesengebirge at Jannowitz, about 10 A.M. on July 16, 1921. He found the following values of relative humidity:

At a height of 6 cm in a widespread stand of oxalis	84%
At a height of 30 cm between myosotis	67%
At a height of 100 cm in the open forest	59%

The input of water vapor from the forest floor and from the crown modifies the drying effect of the outer air which attempts to penetrate the interior of the stand. A "midday type" takes form (T_2 in Fig. 154) two maxima of relative humidity, one above the other. The lower one is caused by water received from the forest floor; the other, by that from the tree-tops. Since in the upper part of the crown there is constant intermixture with the outer air, the latter maximum appears to be displaced downward to the lower edge of the crown space.

While the curve T_1 falls within the range of high humidity (drying begins only at the top), and T_2 at the time of midday minimum, T_3 has an intermediate position. It represents the evening type of humidity distribution. While at this time the air above the crown is still completely under the dominance of the drying daytime hours, the steady transfer of water vapor from the ground begins to be more effective as the temperature decreases in the shady forest with the more oblique rays of the sun. At this time consequently there occur the greatest humidity differences at the different heights. Under such conditions I have observed differences of as much as 25% between the forest floor and the air just above the crown.

The types of humidity distribution described, explain at once the daily march of humidity which is represented in Fig. 155 in a manner similar to that used for the temperature in Fig. 152.

The difference in the daily range of relative humidity between crown space and forest depths (shown at the lower edge of the chart) is this: From its lowest value at the time of the morning temperature minimum, when all layers are close to saturation, the difference rises about 5% at daybreak and until midday remains at approximately this point. In the late afternoon it again begins to increase and reaches a point which is, on the average, between 15 and 20%. From then on, the difference decreases steadily until it again reaches its minimum between midnight and sunrise.

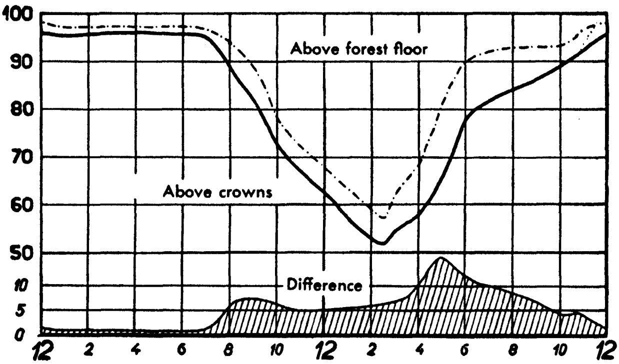

Fig. 155. Diurnal course of relative humidity in a pine grove. (After R. Geiger)

The daily minimum of relative humidity coincides with the temperature maximum, which occurs at about 2 P.M. Because it is at about this time that the difference between the relative humidities in the upper and the lower part of the forest first begins its afternoon ascent to a maximum, observations confined to the daily extreme values of relative humidity in the different layers of the forest would show only slight differences. The advantage possessed by the forest plant over that growing in the open, consists only partially in the higher daily minimum of relative humidity in the forest and much more in the long duration of the humidity surplus, which in the evening hours can attain a considerable height.

By using thermoelements which he kept moist, H. Ungeheuer also obtained the atmospheric humidity. As an average of 126 calm, clear, summer days the following values of relative humidity at the different hours of the day were obtained:—

TABLE 53

Height above the forest floor m	Hour of the day											
	1	3	5	7	9	11	13	15	17	19	21	23
17	**81**	**82**	83	80	77	73	67	65	69	76	79	**81**
11	80	80	**83**	81	78	73	69	67	72	77	**79**	80
3	80	80	**83**	**83**	**80**	**77**	**71**	**69**	**73**	**78**	78	79
0.3	**82**	**82**	83	82	78	74	68	65	69	76	**80**	**83**

The lowest humidity during the 24 hours occurs everywhere at 3 P.M. The dampest measuring places at a given hour are emphasized by **bold** type. Day and night differ considerably. Throughout the day and evening the wettest layer is not at the ground, as shown in Type T_2 and Type T_3, but 3 m above. At night the two surfaces which dispense water vapor become prominent, and it is noteworthy that the maximum at the ground has almost the same value as that in the crown. In both cases the air layer next to the forest floor appears dry in comparison with results hitherto given. The reason for this is the great scarcity of plants on the floor of the forest. For the most part the ground was covered with yellow, but not rotting, leaves. It is also possible that the slope wind, which could sweep through the forest, had something to do with it.

CHAPTER 32

Wind and Precipitation in an Old Stand

Just as insolation falls on the surface of the stand from outside, so does wind movement from outside impinge upon the forest. We shall for the present disregard the case of a stand where the wind blows through from the side, and confine our attention at first to relationships in an old, close stand.

Anyone passing through the forest when the wind is strong and gusty will notice that first of all the roar of the storm is heard over the forest; several seconds later the tree tops begin to wave and a little later still the increased movement of the air is felt, directly. This lag in storm force from the top downward, which is caused by the baffle action of the forest, is accompanied by a reduction of its intensity. A stormy gust above the crown is felt within the stand as only a slight breeze.

We have a series of measurements of the vertical distribution of wind speeds made by R. Geiger (*649*) in a 15 m pine stand. Six four-cup anemometers, operating for 188 hrs. showed the following mean air-speeds: —

TABLE 54

Height of the anemometer m	Position of anemometer	Average wind speed m/sec.
16.85	Above the tree tops	1.61
13.70	Upper limit of tree tops	0.90
10.55	In the tree tops	0.69
7.40	Upper part of trunk space	0.67
4.25	Within trunk space	0.69
1.10	Over the forest floor	0.60

This shows that the reduction in wind speed is principally in the crown space. From the lower limit of the crown down to just above the ground there prevails an astonishingly uniform, gentle air movement. Only below one meter is there another reduction, bringing the speed on the ground to zero. The greater part of the wind's kinetic energy is, therefore, like radiant heat energy, consumed at the crown roof and only a small part at the ground.

This is seen still more clearly if the above-given wind measurements are arranged according to speed. Fig. 156 shows the variation of velocity with height for three groups of wind forces. With gentle winds the braking appears only in the crown space, but with stronger winds (curve at the right) a freshening of the wind in the trunk space at a height of about 7 m is noticeable. From thence downward the speed diminishes until stopped by the ground.

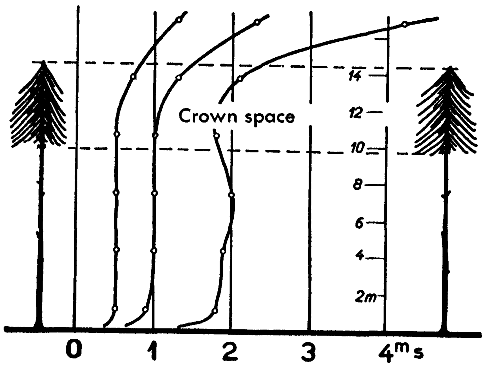

FIG. 156. Distribution of wind speed in a pine grove

Longer and more recent series of measurements have been carried out by R. Geiger and H. Amann (650), in the previously mentioned old oak stand at Schweinfurt. The records were made partly in the springs of 1928 and 1929 before the leaves were out, and partly then and in the fall of 1928 after the leaves were out on the lofty oaks and lower beeches. The results demonstrate the effect of leaf development.

Fig. 157 shows the wind distribution in each case. Before the leaves are out it is naturally easier for the wind to penetrate the bare stand. To be sure, there is a braking action evident in the crown space, since there the twigs and branches are thicker. But down through the whole trunk space there is a slight decline of velocity. On the other hand, once the million leaves have unfolded, the trunk space is virtually stagnant. A noteworthy consequence of this is that above the crown the wind blows even more strongly, as Fig. 157 shows.

The plants of the trunk space enjoy great quiet, which protects, but also spoils them. This is best appreciated if one calculates the number of calm hours in the Schweinfurt series of measurements.

Expressed in percentage of all hours recorded (206 before leafing, 494 after leafing) it amounts to:

TABLE 55

Height above the forest floor	Position of the anemometer	Number of calm hrs. (%) Before Leafing	After Leafing
27	Above the crown	0	10
24	In the crown	8	33
20	Lower edge of crown	35	86
4	Above the forest floor	67	98

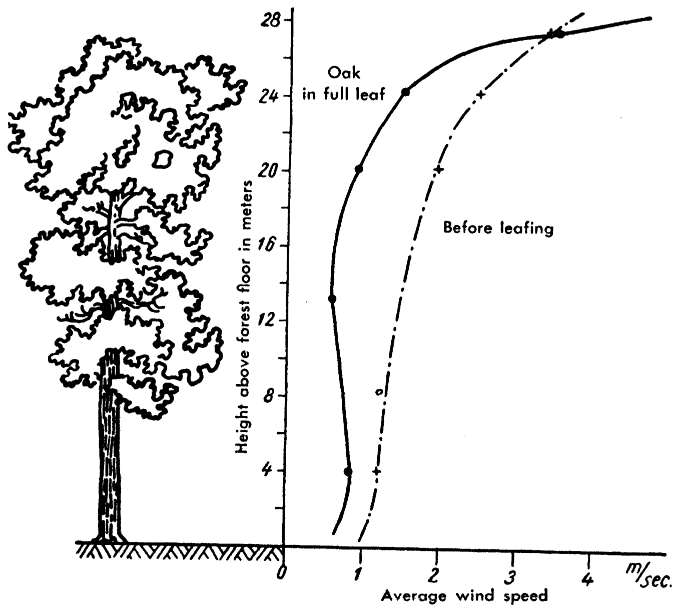

FIG. 157. Influence of the condition of foliage on the distribution of wind speed in an oak grove with beech under growth. (After R. Geiger and H. Amann)

By calm hours are understood those in which the anemometer, which has a starting speed of 0.7 m per sec, did not move.

Now what does the forest do with the precipitation that falls on it?

The rain — which we shall consider first — first wets the crown with its countless leaves or needles and twigs. If the rain is very

light, in fine drops and of short duration, this is as far as it gets into the forest. But as soon as the precipitation gets a little heavier, the water is passed on when the crown is thoroughly wet. Part is conducted by twigs and branches to the trunk and runs down. All the remaining falls to the ground.

It was early recognized that one cannot say of a rain measurement merely that it was made "in the forest." It depends on where the rain-gauge stands. E. Hoppe's (*651*) careful, inclusive research has shown that with the formerly practiced installation of a single gauge beneath the crown of a tree, an average error of from 25 to 30% in the measurements must be expected as a result of chance variations in exposure. For a single measurement the error may amount to far more than 100%. With a light rainfall, no relation can be shown between the amount caught by a single gauge and the "true rainfall" which E. Hoppe determined by 20 raingauges arranged within the stand in two rows crossing one another at right angles.

Fig. 158 makes clear the distribution of rain within a stand, according to the data of E. Hoppe. Let us first consider the evergreen forest, the observations were made in a 60 year old spruce stand. With light rainfalls (up to 5 mm) two thirds of the whole amount of rain is caught by the crown. The heavier, and usually the longer lasting, the rain, the less (as is easily understood) the proportion which is used in wetting the tree crown. It is worthy of note that even with the heaviest rainfall a fifth of it never reaches the inside of the forest. As to the water that runs down the tree trunks, it does not amount to much — less than 5% even in a cloudburst. The amount which drops through the crown and so reaches the ground, only in rainfalls over 10 mm amounts to half that which falls on the forest. This portion which drops through, is unevenly distributed within the forest. It is least close to the trunk and increases toward the periphery of the tree. This is shown by the following figures from the same stand, which give — for all rainfalls, irrespective of strength — the precipitation at specified distances from the trunk, as a percentage of the rain falling on the forest: —

Distance from the trunk in meters	0 to ½	½ to 1	1 to 1½	Over 1½	Near Openings
Percentage	55	60	63	66	76

Let us now return to the observations made in an 88 year old beech forest (Lower part of Fig. 158). That part of the rainfall which clings to the leaves is relatively much less in a deciduous forest than

in an evergreen stand. With the greater density of the leafy canopy this at first seems surprising, but this is the answer: While the drops remain hanging on the separate spruce needles, they flow together on the beech leaves and pass over twigs and branches to the trunks and from there downward. Consequently the proportion of the rain dropping through the crown amounts to more than 50%, even with the weakest rainfall and the quantity running down the trunk

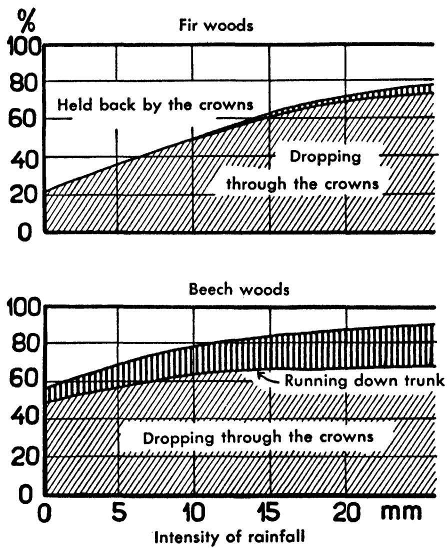

FIG. 158. Distribution of rain in narrow and broad-leafed forests. (After E. Hoppe)

amounts to a fifth of the total. According to a report contained in a letter from F. Sauberer, still more recent measurements by H. Friedel at Lunz have shown different relationships in that in a beech forest in full leaf the downflow of water at the trunk begins only after quite heavy falls of rain. As long as precipitation in the open does not exceed 10 mm the portion which runs down the trunk is said to be negligible. So far as I know this has not been published.

As to the distribution of snow in an old stand, we unfortunately possess no such conclusive series of measurements as for rain. From comparative observations of snow depth in a stand and in the open, such as J. Schubert (*624, 627*) reported for the duplicate forest stations of Prussia, it may be concluded that most of the snow falling on the stand gets to the forest floor. While the ratio of rain outside

to that inside the forest, as an average of 120 years from many pairs of stations, was 100 to 73, the ratio for snow was 100 to 90. The snow measurements of H. Hesselman (*669*) in Sweden show nearly the same depth of snow in a pine forest as in cuttings. In any case snow reaches the floor of the forest more easily than does rain. One reason is that snow which accumulates on the crown branches breaks away by its weight and falls to the ground. Moreover, low temperatures prevent any great loss through evaporation directly after a snowfall, such as occurs after a summer rain.

G. Priehäusser (*652a*) made some exceptionally fine observations on snow relationships in spruce stands of all ages in the Bavarian forest. He showed how frost saucers form under single spruces in the course of the winter. Ground frost begins where the side branches are bent down to the ground by the snow, and increases rapidly in strength toward the bare inside of the protected area. Open portions of an old spruce stand receive the full depth of snow, which does not blow away. Under the protection of single spruces only powder snow reaches the ground. Close spruce stands support a porous cover of dropping snow. Particulars may be obtained from the publication mentioned.

CHAPTER 33

The Influence of Make-up of the Stand on Its Climate

Forest meteorology, as mentioned in Chapter 29, was, in the 19th century, merely an adjunct of forestry management. Today, as forest microclimatology, it is called on to serve as an auxiliary science in forest building. As it is now a self evident fact to the forest scientist and practical man that he should take soil conditions into consideration as a habitat factor in cultivation, so is this increasingly true as a habitat factor in microclimatology.

In the service of practical forest building the science of microclimatology directs its attention not only to the type of stand climate as described in the three preceding chapters, but far more to the variations from this type which reforestation projects have occasioned. Much has already been accomplished in this new field of endeavor. In this and the two following chapters we can give only a survey showing in what direction development is proceeding. It should give an extended hand of encouragement to everyone who has learned to foresee the significance and wonderful future of this practical science.

First we shall accompany H. G. Koch (*670*) on a fair-weather temperature measuring expedition in a motorcar through a forest district in the neighborhood of Leipzig in order to get a firsthand impression of the changing temperatures one finds in different kinds of stands. In Fig. 159, at the top, is presented a cross-section through the country, showing the various stands traversed. The daily temperature march for July 8th and 9th, 1933 is given below in isopleths. The times of sunrise and sunset are indicated by broken lines. At these transition periods between day and night the isotherms crowd together and lie practically horizontal. This means that at those times the temperature is undergoing a great, and everywhere similar, change. The temperature fall at evening and rise in the morning are meteorological occurrences of such magnitude as to overshadow differences within the stand.

At the times however when the heat exchange reaches equilibrium, local peculiarities become effective. This is much more true at night than at midday, for Fig. 159 shows that the "islands" in the isotherm map are more sharply outlined at night than at midday. The cause of this is the greater quiet of the night air and its thermally stable stratification. About noon the temperature is above 25°C in

three places — they are, as a glance at the upper sketch shows, the clearings, stretches of open land and nursery areas. On these same areas it is very cold at night. At several places on the islands it is below 11 °C.

R. Geiger (649) was the first to carry out comparative measurements in old stands of the Wondreb forest district, which were similar as to situation and previous history, but variously treated as

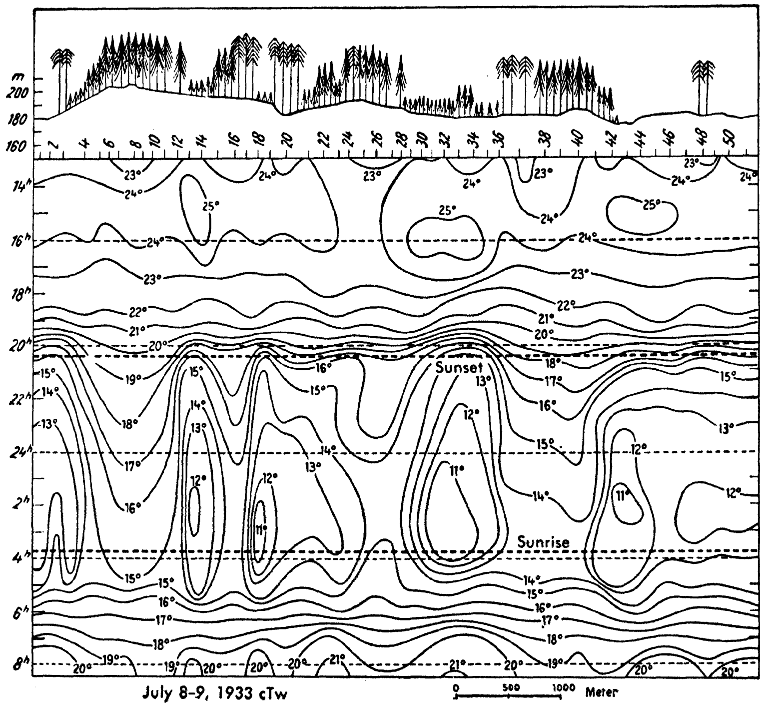

FIG. 159. Diurnal course of temperature within an enclosed forest region at Leipzig. (After H. G. Koch)

to upbuilding. The problem to be investigated was the numerical determination of the microclimate difference between a stand with a uniform crown canopy and a stand with varying height. One portion of a 65 year old pine stand (designated as I) had a loosely closed, uniform crown; the other portion (II) was thickly undergrown with spruce so that there were tree tops at all levels. This latter portion had, as the forester says, "step closure." The observa-

tions in the two adjacent portions of the stand were made with the aid of two observation scaffolds such as are depicted in Fig. 144.

Although the two places were only 86 m apart, the stand climates proved to be very different. The air in the trunk space of II, on account of the numerous crowns, reacted more slowly to the penetra-

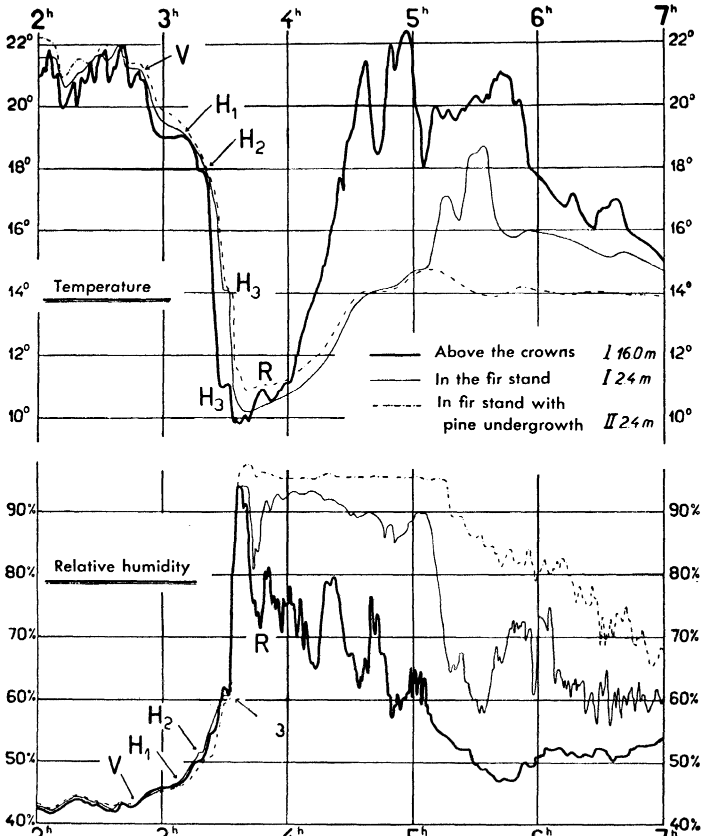

FIG. 160. The penetration of cold thunder storm air in two neighboring but differently constituted forest stands

tion of the outside air than did that of the pure pine stand I. This can best be demonstrated by a lag test which Nature herself carried out.

When a thunderstorm broke on the afternoon of May 21, 1925, after a hot morning, the temperature and humidity showed the

curves reproduced in Fig. 160. The inrush of cold air can be followed through its separate phases. First came a weak forerunner (V) then, in three steps, the squall itself (H_1–H_3), followed by a small return of warm air (R). The forest air in both stands followed this sudden change of condition with a certain delay. This is most evident in the case of the third step (H_3) for at the onset of H_3 the temperature above the stand had already dropped to 11°, while in the stand it had reached only 14°C.

The greater lag in the reaction of stand II appears clearly in the following particulars:

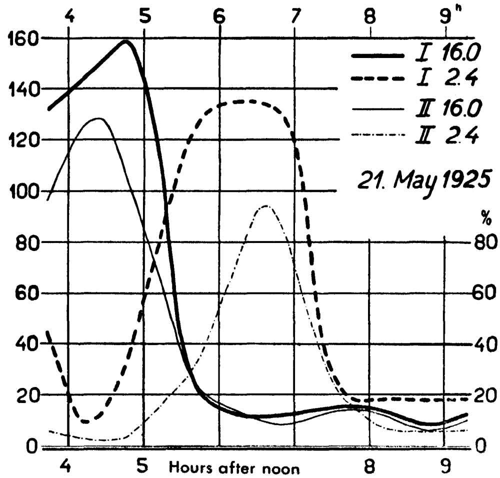

FIG. 161. Combat of the humid air of the trunk region with the dry open air in the same thunder storm

1. The temperature minimum above the stands was 9.6°. In the trunk space of I it was 10.3°; in that of II, it was 10.8°. The temperature maximum which was attained some time after the inrush of cold, was 22.4° above the crowns (sunshine again prevailed over the crown canopy). In stand I it was 18.7°; in II, only 14.6°C.

2. The first recoil of dry outer air brought a drop in humidity of 25% above the crowns; within stand I, 13%; while within II it was hardly noticeable.

3. From the time of the cold air invasion until the late hours of the evening, stand II held its internal moisture better than did stand I. (The dot and dash curve at the bottom of Fig. 160 remains

continuously somewhat above the thin, solid line.)

The contest between the dry outer air and the moist interior of the forest is made still clearer for us by Fig. 161. The ordinate represents the sum of the hourly humidity variations without regard to their sign. The two solid lines representing conditions above the stand have their maximum one to two hours earlier than the broken-line curves which represent conditions within the forest.

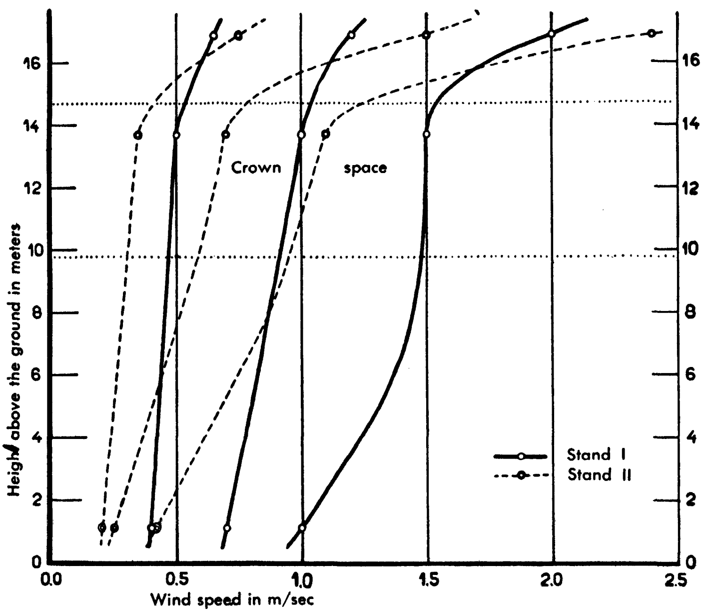

FIG. 162. Average wind speed in two neighboring but differently constituted forest stands

The struggle between the different air masses displays itself in the very unsettled state of the humidity, for now moister and now drier portions of air stream pass the instrument. It began at the very top of the forest. Shortly after 6 P.M. the struggle had penetrated the pure pine stand I; later and with diminished energy it made itself felt in part II, the lower portion of which was filled with spruce.

The different climatic lag of the two forest plantings which was clear to us in the records described, now expresses itself in all the climatic factors — most clearly in the average wind velocity. Fig. 162 reproduces the curves for three different velocity levels in each

stand. In stand I the wind is uniform above and below; in II it blows unhindered above the crown while within the stand it is much quieter.

The temperature relationships are more complicated.

At the hottest time of day the close stand II remains on the average as much as 2°C cooler than stand I. As to the vertical temperature distribution, the hottest zone in I extends down into the crown space on account of the relatively good air mixing, while in II it remains above the crown canopy. But, since the incident and absorbed solar energy is the same in the two adjacent stands, the lower temperature within stand II is balanced by a higher maximum above the crown.

Just as by day the interior of the spruce-filled stand II is relatively cool in comparison with I, so by night it is relatively warm, and the relationship above the crown is again reversed. The lag of the minimum within II is somewhat greater than within stand I, in contrast with the appearance of the minimum above the crown.

Evaporation in the two stands, as calculated from temperature, vapor pressure and wind according to Trabert's formula, was as follows — the amount in the open being taken as 100:

TABLE 56

Height	Stand I Pure Pine	Stand II (Pine and spruce)
16.0 m (above the crown)	103	100
12.6 m (in the crown space)	94	68
2.4 m (in the trunk space)	71	43

The habitat climates of the two neighboring stands are, therefore, as appears in all that has been said, very different — showing how great an influence the forester has through his varying management.

In 1927–30 R. Geiger and H. Amann (650) made similar comparisons in a light old oak stand, with and without beech undergrowth, in the Schweinfurt forest district. In 1927–8, H. Burger (658) compared the trunk space climates in a spruce stand of uniform age and a nearby fir-spruce "blended" (intertilled) forest at Thur in the canton of Bern. A. Ångström (655) in 1925–34 determined the influence of different densities of planting on the temperature of the forest floor at depths of 15, 30 and 45 cm. Several years of observations at Vindeln in North Sweden showed that in thickly planted stands the ground temperature was 2 to 3° higher than in the thinner stands

and that, correspondingly, in the spring the ground thawed out 2 to 4 weeks earlier. In 1935–36 Boos (*657*), at Erdmannshausen, compared the forest floor temperature (as well as humidity, wind and precipitation in the air near the ground) in two pine-spruce mixed stands and two beech stands.

In a mixed stand of pine, spruce with a few firs and beeches, in the Jura region C. von Wrede (*684*) in 1923–4 investigated the climatic difference of openings and thinned strips. In a portion of the forest thickly filled with undergrowth an opening was cut; i.e. a very small clearing made within the old stand — in the present case circular with a diameter of 13 to 14 m — on which the young growth of the next forest generation could grow up under the protection of the old generation. Quite nearby an east-west thinned strip, 50 to 60 m wide had been laid out, where so many single trees had been removed from the close forest that the ground was only about 43% covered by crowns ("degree of stocking" = 0.43). The light which fell on the opened stand permitted the young growth to rise on the forest floor.

In the midst alike of opening and thinning C. von Wrede erected an observation shelter 40 cm above the ground, in order to determine the conditions in the airspace near the ground in which the young growth had to develop. Temperature measurements indicated a more moderate climate in the opening than under the screen strips as the following figures show:

TABLE 57

	Difference of absolute monthly extremes		Greatest daily temperature range in month	
1923	Opening	Screen	Opening	Screen
June	18.1	20.9	12.5	15.5
July	23.6	26.7	15.0	16.7
August	24.0	27.9	20.6	24.0

The cause lies in the wind relationships. Cup anemometers were placed 1 m above the ground and the wind motion was read off according to the final observations. The average wind speeds were:

TABLE 58

In the month of	June	July	August	September 1923
In the opening	0.26	0.50	0.55	0.35 m per sec.
Under the screen	0.54	0.85	0.72	0.49 m per sec.

The wind speed under the thinned strip averaged 1½ times greater than in the opening. In addition the wind direction observed in the opening was for the most part just the opposite of that in the open. We must imagine the wind circulation in opening and thinned strip is as shown in Fig. 163. A whirl forms amid the surrounding, protective old stand. The upper wind reaches in only partially and the whirl causes the frequent reversal of wind direction at the ground. H. Pfeiffer (*676*) meantime has been investigat-

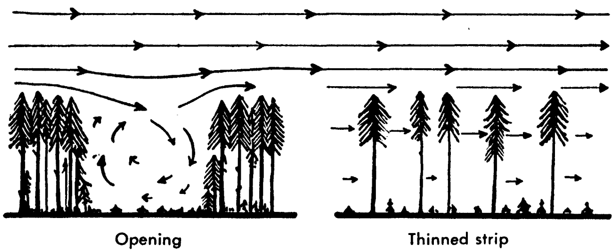

FIG. 163. Wind movement in an opening and in a thinned strip

ing this air movement directly by means of smoke experiments (see Chapter 35). It is of great practical significance where there are courtyards within great blocks of houses. If in Fig. 163 we imagine the surrounding forest at the left replaced by houses, we can readily understand that the chimneys in the houses at the right will not draw properly, and that in those dwellings the fire will often be driven out the stove doors. In such cases it helps to plant trees in the courtyard to hinder the formation of whirls.

If the air cannot penetrate the opening, neither can the sun; so the air does not warm from the ground upward, but rather from the stand outward as is proved by temperature measurements near the ground (*179*). On the other hand, so much insolation reaches the forest floor through the loose crown of the thinned strip that the air warms from the ground up. Beneath the thinned strip the relative humidity of the air was from 5 to 7% less than in the opening.

H. Amann (*793*), also, has made meteorological studies of the influence of a screen stand. We shall come back to this subject in Chapter 40, in connection with the question of frost.

CHAPTER 34

The Microclimate of Circular Slashings, Clearings and Cuttings

The forester likes to rejuvenate his stands by means of *hole cuttings* or *hole slashings* (usually circular areas) in the old stands. The moderate temperature range, the high atmospheric humidity and the calm air of the surrounding trunk space, characterize the habitat climate of the hole cutting as well. From the very beginning the young growth finds there the climatic conditions favorable to its development. We have already met such a hole cutting, in the preceding chapter, in the "opening" of von Wrede's studies.

Young ground plants require both light and sun to flourish, consequently there is an effort to enlarge the openings. Moreover the necessity to give the future generation sufficient space leads to the same end. But, as the size of the openings increases, their microclimate alters. The greater penetration of insolation by day and the increased outgoing radiation by night result in extreme ground temperatures, which, on account of the quiet air, are able to make their influence felt to the full in the habitat climate over the forest floor. For this reason the larger clearings are indeed very warm by day, yet on spring nights they are very much in danger of frost, which is a real hindrance to their practical usefulness in certain macroclimatic areas.

The larger the hole cutting is made, up to the point where it deserves the name of forest clearing, the more the wind from above can reach into it, down to the air next to the ground. This signifies a reduction of the daily temperature range and a lessening of the frost danger. In the transition from a narrow hole slashing to a broad clearing it is to be expected that at some certain size the habitat climate will be particularly extreme. Below this critical size the climate is milder on account of less radiation; above this size, on account of less quiet air. It is not the diameter D of the clearing which is the effective dimension, but its ratio to the height H of the surrounding stand. This ratio D:H we call farther on the "index size of the clearing."

The outgoing radiation A in the midst of a circular clearing may be calculated, according to F. Lauscher (*63*), in percentage of radiation in the open from the mean screening angle (h) by means of the formula

$$A = 100\,(1 - \sin^{r+2} h).$$

Here r is a function of the observed vapor pressure e which can be represented with sufficient accuracy by the equation $r = 0.11 + 0.034\,e$. The screening angle h is to be measured from the ground at the middle of the clearing. Calculating this from $\tan h = 2H/D$ gives too large values of h, as R. Geiger showed (*667*) for the horizon of a hole-cutting is formed not only by the trees at the border, but (where there are gaps in the front row) by the tops of trees farther back.

As to the calmness of the air in the clearings, we have good witness in numerous temperature measurements of earlier days. In 1872 P. la Cour (*659*) showed that forests are surrounded by a belt of increased temperature fluctuations. This is chiefly a result of heightened radiation effect by reason of greater calmness of the air. According to C. G. Bates (*715*), windbreak strips increase the daily range by 5°. Somewhat later, H. E. Hamberg (*602*), in his classic investigation into the influence of forests on the climate of Sweden, showed that clearings possess a climate of greater extremes than that of the open. J. Schubert (*626*), in connection with observations in Neumark from 1900 to 1903, found 9.4° as the daily temperature range in the trunk space during August and September, 9.9° in nearby open country and 10.8° in a shelter within the clearing.

B. Danckelmann (*660*) discovered an increase of frost danger with increase in size of clearings, as a result of observations in the Mark forest. In 1894 clearings up to an index size of 1¼ showed complete or nearly complete freedom from frost; with an index of 1½ the danger was still within reasonable limits; but with an index of 2 or more the frost danger was great. This result depends naturally on the accidental frequency of late frosts during the period of observation.

R. Geiger (*667*), in 1940, carried out a systematic series of experiments in a 26 m mixed stand of pine and beech at Eberwald. Seven circular cuttings of different diameters had been made in the stand. The following table gives the relative sizes and the result of a number of measurements:

TABLE 59

Diameter D in m	0	12	22	24	38	47	87
Index size D/H	0	0.46	0.85	0.93	1.47	1.82	3.36
Average screening angle h	90°	72°	59°	58°	48°	40°	26°
Outward radiation (% of that in Open)	0	11	31	33	52	66	87
Rain (% of that in open)		87%			105%		102%
Midday temperature (8 June 1940) (amount warmer than the stand)	0	0.7	1.6	2.0	5.2	5.4	4.1

The index sizes had been selected to extend beyond 3. As a result the outgoing radiation in the largest clearing amounted to within 13% of open country figures, so that the investigation embraced all the values likely to be encountered under practical forest conditions.

The result of rainfall measurements during the months of June through Sept. 1940, was that in each month the least rainfall occurred in the smallest clearing, for rain which fell slantingly was more or less caught by the crowns of the surrounding trees. The greatest amounts were caught by the 38 m cutting; its bordering trees stood back so far from the center that they did not obstruct the rain. The effect of the quiet air was, that, on the average, 5% more rain was caught than in the open. In the 87 m clearing the excess was only 2%. The clearing with the 1.5 index therefore represented a critical size — with respect to the above mentioned characteristics.

Similar relationships appeared for the temperature measurements, which were made on a sunny day, using an aspiration thermometer in the middle of the clearings at a point 10 cm above the ground. The table indicates how much warmer the clearing was than the surrounding stand. The values reach a maximum for indices from 1.5 to 2.0 and then decline markedly.

The results of night temperature observations give a different picture entirely. Fig. 164 shows that the temperature declines uniformly as the diameter of the clearing increases. This is as true for the mean of the 17 coldest nights in the spring and summer of 1940 as for the coldest late frost night of the year, which occurred on June 6. It is well known that calm, radiation nights are the dangerous ones for late frosts, so that there is no noticeable effect of wind on temperatures. Perhaps the critical size is found only above an index of 3.4 or — what is more probable — the straight line in Fig. 164, as the index rises, approaches asymptotically the nocturnal temperature minimum of open country. That it is not merely outgoing radiation which is in control, appears, however, in that the tempera-

ture fall is not proportional to the published radiation values *A*. There must be in addition either a warming influence in connection with the small clearings or a cooling influence in connection with the large ones. The former is accounted for by the mixing of the cold air in the clearing with the warmer air from the trunk space;

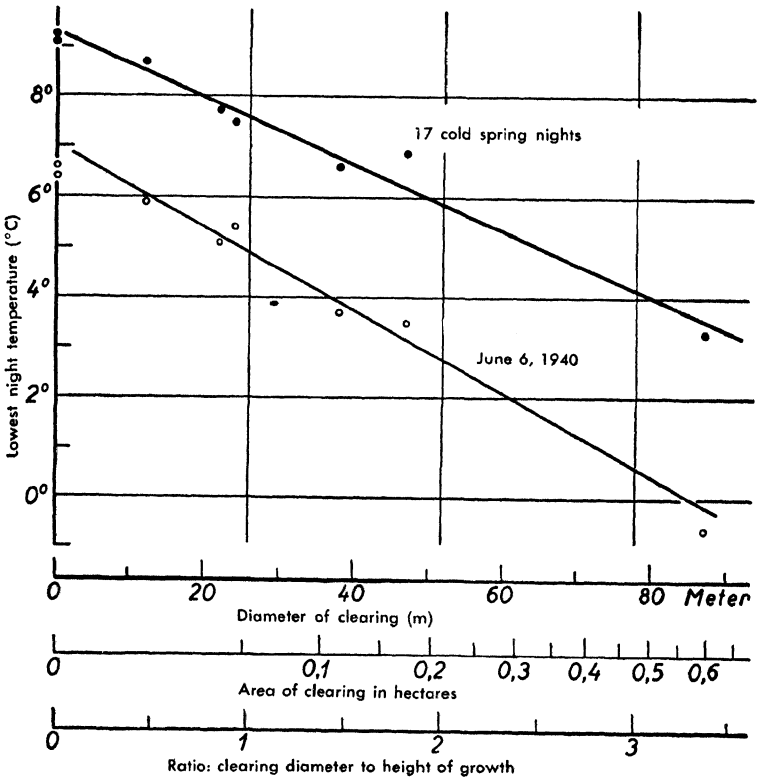

FIG. 164. Increase of frost danger in clearings of increasing size

the latter, by the descent into the clearing of air which has been cooled above the crowns of the surrounding stand — a process which in the following chapter we shall designate as a "nocturnal forest wind."

Outgoing radiation relationships in narrow openings and forest cuttings (also called lots or spacious glades) can be computed according to the suggestion of F. Lauscher (*63*). If *h* be the screening angle, looking outward from the middle of the cutting toward the

stands (considered as of uniform height on both sides), then the outgoing radiation from the cutting S in percentage of radiation in the open can be calculated from the following figures:

h:	0	5	10	15	20	30	45	60	75
S:	100	93	86	80	74	62	45	30	14

F. Lauscher and W. Schwabl (*642*) have studied the diurnal illumination conditions in such cuttings. Fig. 165 shows measurements made at Lunz in a north and south cutting, 20 m wide, in a 80 to 100 year old mixed stand of spruce, fir and beech. The illumina-

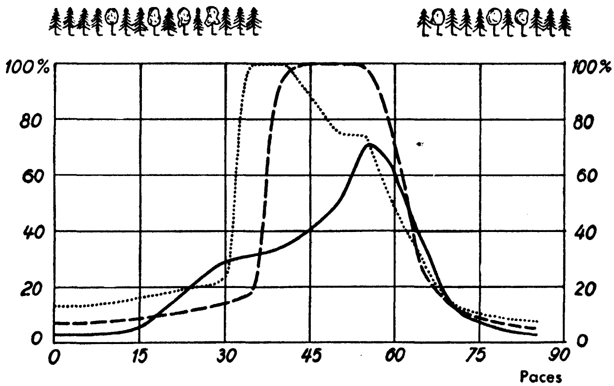

FIG. 165. Illumination conditions in a N-S- directed forest cutting. (After measurements by F. Lauscher and W. Schwabl)

tion values, which were obtained with barrier layer photocells, are expressed in percentage of those simultaneously observed in the open. As the sketch indicates, the cutting extended between points 35 and 63 (number of paces) on the ordinate scale. It is seen from the north, so that east is at the left and west at the right. The broken line and the dotted one were obtained in sunshine. The maximum brightness is as great as in the open but its location in the cutting varies with the movement of the sun. The solid line represents a measurement with cloudy sky. In that case it is not the direct insolation but the sky radiation (analogous to nocturnal conditions) which determines the illumination; it consequently reaches at no point the brightness of open country conditions, as it does in clear weather.

E. Schimitschek (*680*) has made some estimates as to the sunnyness of wedge cuttings.

Wind conditions in cuttings have been investigated in the Anzing-Ebersberg forest by R. Geiger (664) and later by H. Pfeiffer (676) using models in a wind tunnel.

Fig. 166 shows schematically the results of Geiger's measurements. The heavy arrow represents the wind aloft, *over* the cutting;

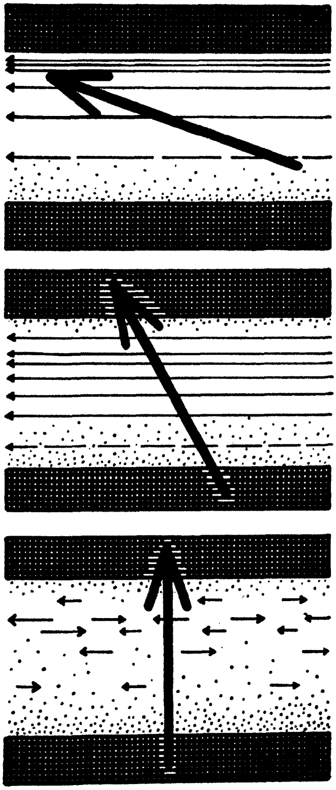

FIG. 166. The wind motion in a forest cutting in relationship to the upper wind

the small arrows, the winds *in* the cutting. The stronger the winds, the closer the lines. Dotted areas indicate dead air spaces. If the wind is blowing perpendicular to the course of the cutting the wind gusts above the cutting are indicated by opposing pairs of arrows. The wind whirl shown in a clearing formation (Fig. 163) can also be observed in a cutting; in such case the wind at the ground is blowing opposite to the general direction. There may even be a

double whirl (one above the other) as H. Pfeiffer has determined. In this case the wind at the ground, just as in the trunk space, blows in the common direction while at half the height of the surrounding stands there is a countercurrent.

When the wind blows down aslant into the cutting, the maximum velocity is displaced from the wind-sheltered side toward the stand which bears the blast of the wind, just as in the case of light the maximum brightness is displaced from the shaded side toward the opposite one. If the wind moves approximately along the axis of the cutting there ensues a decided maximum speed at the edge of the stand, which guides the wind.

CHAPTER 35

The Climate of the Stand Border

Great significance from the point of view of forest building is attached to the climate of the border areas for the forester usually renews his stands at the edge of the old wood. For this purpose he makes use of the outer edge, that is, the strip of open land beyond the forest, and also the inner edge, which lies beneath the bordering trees of the stand.

The climate at the stand border results, as R. Geiger (*666*) has stated, from two fundamentally different causes. In the first place it is a transition climate between that of the trunk space and that of open country. The contrast between the two leads to an exchange of their properties. The influence of the trunk space climate predominates on the outer edge; the open country climate, on the inner edge. In the second place, the edge of the stand is like a high step in the land. According to the direction it faces, it catches insolation or it withholds it from the open country. It catches the wind and opposes itself to rain or snow. Insofar as the stand border is in the "shadow" of the wind, it protects the open country and may lessen or increase its precipitation.

The second list of causes are the more effective in their action. The most powerful factor among them is the daytime radiation of heat, which we shall describe first. The diffuse sky radiation is really ineffective for it acts on stand borders in all directions without distinction. The greater the ratio of sky radiation to total radiation, so much the less difference is there between the various stand borders (compare what was said in Chapt. 22 with regard to slope climate). This applies in cloudy weather and in northern countries. Only *direct* insolation causes differences.

Fig. 167 shows the duration of sunshine for stand borders in all directions and at all seasons. It is based on the 1895–1934 series of observations at Karlsruhe, from the work of J. von Kienle (*429*). The number of sunshine hours refers to a month as unity. The irregularity of the curves reflects the changing weather conditions, which even in the 40 year mean are not entirely smoothed out. Looking at the picture as a whole there is symmetry on the one hand between spring and autumn conditions, and, on the other,

between the relations of east and of west borders to that on the south. The four black corner areas belong to the borders which face the north and which have no sun in winter. The longest duration of sunshine is found in midsummer on the southern exposures (in contrast to sunshine intensity as discussed in Chapter 21). Along the stand borders from SW through S to SE the duration of sun-

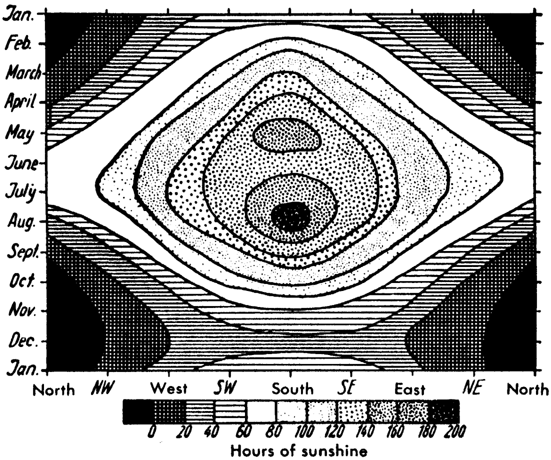

FIG. 167. Monthly duration of sunshine on the edge of a stand from all directions in relationship to the time of year. (After calculations by J. U. Kienle)

shine from the beginning of May to the end of August exceeds 150 hours per month. In this region there are two maxima, separated by the bad weather of June, which as the "European monsoon" usually brings more clouds and precipitation than does May with its pure air, and August which already reaches toward the clear autumn days of "Indian summer."

The figures cited by J. Schubert for intensity of irradiation will serve to give some information at least for the stand borders which face in the four main directions. They too are based on measurements in which average conditions of cloudiness are considered. Reference has already been made to the special position in which south borders stand at the end of winter.

What parts of the borders gain in radiation, the others lose through shading. R. Geiger (665) has furnished some information as to width of shading in front of the stand — assuming level ground. Fig. 168 applies to the summer solstice at the latitude of Munich (48°N).

On the horizontal scale are the directions which each stand margin faces, while on the vertical scale are shown the hours of the day (true sun time). In the inner portion of the chart are the lines of equal width of shade, expressed in units of stand height. The heavy

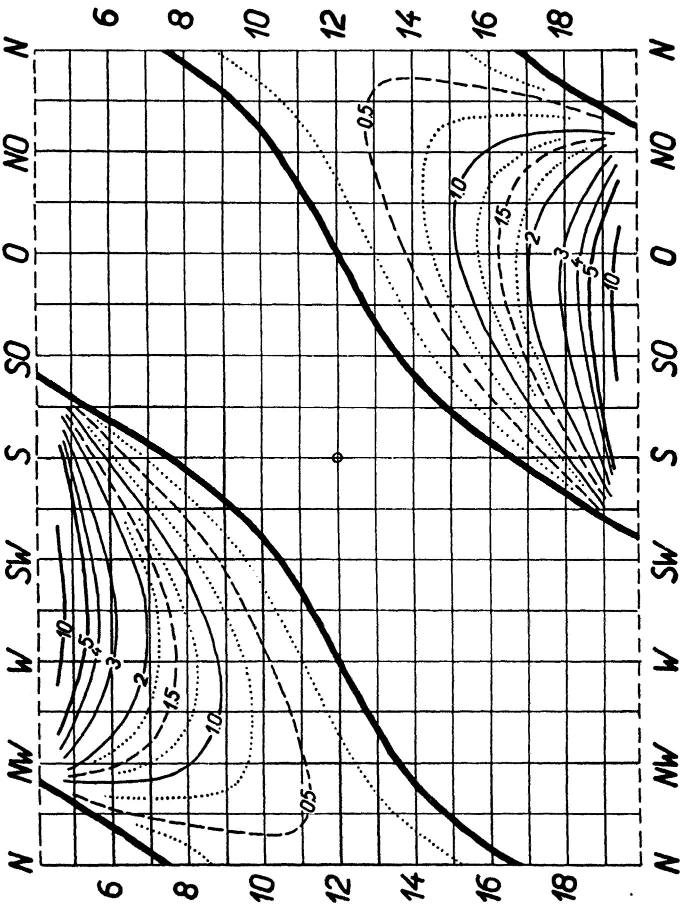

FIG. 168. Lines of equal shadow width in the margin of a wooded region during the time of the summer solstice

border lines between sunshine and shade (zero shade width) unite all the possible conditions under which the sun shines directly along the edge of the stand. The moments of sunrise and sunset are indicated by the upper and lower broken lines. In the areas where the lines of equal width of shade are not extended, the values have no practical significance because the shadows are so long and the sun

so weak. At midday, however, when radiation is strong, the lines are correspondingly closer. It is quite evident that the chart is symmetrical with respect to morning and evening.

From the upper right to the lower left, between the heavy zero lines there stretches the broad white band whose extent indicates full sunshine on the stand margin. In addition there is also an open area at the upper left and at the lower right. This is because in midsummer the sun goes so far north of the east point that it reaches the stand borders which face NNW. These consequently receive sunshine in the very early morning and also a second time toward evening. The same holds for NNE borders.

If it is desired to determine at what time of day shade covers a cultivated strip 15 m wide in front of a 20 m stand which faces WSW, we see from Fig. 168 that for $x = 15/20 = 0.75$, the crop lies in shade from sunrise till 9 A.M. on June 21st. Shortly after 11, the whole crop comes into the sun and remains so till sunset.

There is a very surprising special case discovered by J. Schubert (*39*) which we must not omit. The width of shade in front of a north margin on March 21st and Sept. 23rd (the equinoxes) is independent of the time of day, so from sunrise to sunset it is constant in amount. The long, slanting shadow of morning and evening is of the same width as the steeper midday shadow, which falls at right angles to the stand margin.

Sunlight and skylight pass into the forest between the marginal trees and there favor the development of the young growth. On the other hand the stand darkens the open country in front of it. Fig. 169 shows the resulting transition according to measurements of F. Lauscher and W. Schwabl (*642*). It depends to a great degree on the lighting conditions how the transition takes place. If the sky is clouded, and the forest (a stand of ash at the left in Fig. 169) is not yet in leaf (curve 1) the brightness outside (= to 100) and inside are not very different. Curve 3 corresponds to the leafless condition in sunshine. The direct radiation is strongly reflected by the branches of the forest so that the differences are considerably more than for curve 1. The shading effect extends farthest into the open when the trees are in full leaf and the sun is unclouded (*4*). The dotted line corresponds to a fully leafed condition with cloudy sky. For other kinds of woods, such as spruce, for instance, the difference of illumination inside and outside is greater as we already know. The transition, however, is about the same; only a heavy stand cover such as spruce has, can cause a particularly darkened border area.

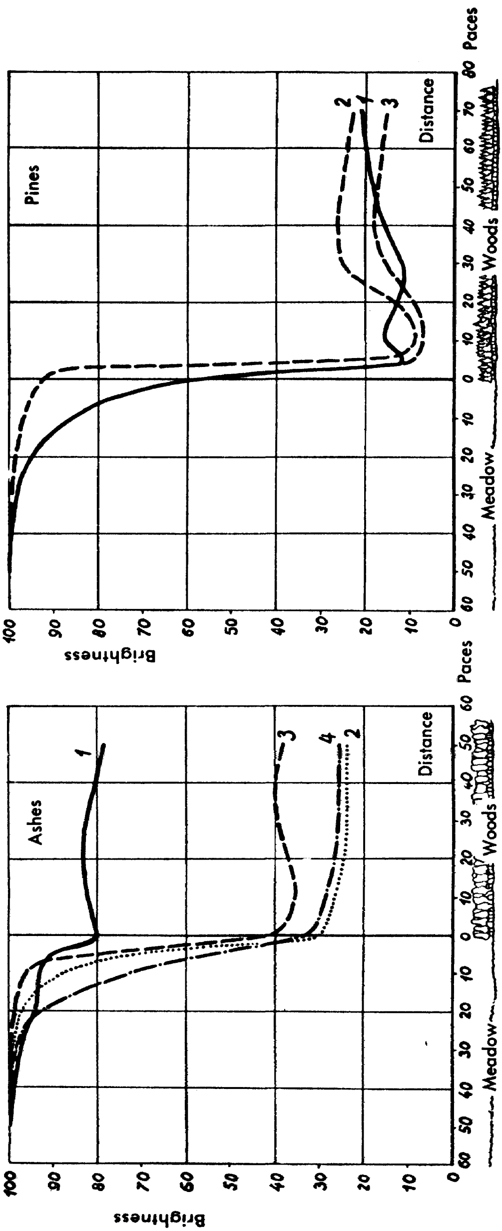

FIG. 169. Darkening of the outer edges and exposure of the inner edges of border of wooded regions. (After F. Lauscher and W. Schwabl)

At night the stand affords the neighboring strip of open land some protection from outgoing radiation according to the research of R. Geiger (*666*). For plants within the over-hang of the trees, half the sky is cut off. The nocturnal net loss by radiation of heat is consequently only half that in the open, for the exchange of radiation with the stand itself is unimportant since the latter has practically the same temperature as the radiating soil. This protection from outgoing radiation, however, decreases very rapidly with distance from the stand. As shown in Chapter 2, this radiation is greatest toward the zenith sky, and access to this is open as we get away from the stand. As a result, at a distance equal to the height of the trees, the counter radiation has already reached 90% of that in the open. It must always be remembered that the frost protection of the border zone near the old wood is caused not only indirectly by reason of the warmer trunk-space air but also directly by reason of diminished net outgoing radiation.

Wind relationships at the stand border become clear if we differentiate — according to the excellent proposal of H. Pfeiffer (*676*) — between an active and a passive forest influence on the wind field.

A passive forest influence consists in the action of the forest as a hindrance to air currents. At the edge of the stand which faces the wind, the currents are forced upward. The consequence is a dead air zone at the ground, estimated at 1½ stand-heights in breadth. Above this the wind speed is somewhat greater on account of the compression of the lifted stream lines. M. Woelfle (*683*) using an Albrecht hot-wire anemometer (*214*), investigated the penetration of the outside wind into a dense stand of spruce. With weak winds, 20 to 30% of the outer velocity was found in the inner *edge*. With brisk winds the protective effect of the mantle increased so that the percentage value decreased. M. Woelfle attributed this to the screening effect of the mantle by which he meant the overlapping of the spruce twigs and the consequently thicker screening of the stand toward the outside.

The wind distribution in the lee of a forest is considered in Chapter 39, in connection with a description of windbreaks. In addition the reader is referred to the rules for wind action in cuttings as given in the preceding chapter.

The temperature action exerted by the forest is an active influence bearing on the wind distribution. This is a question of winds which the forest itself generates.

When during the day the air layer near the ground becomes heated over the open country but remains cool in the forest under

the screen of the tree tops, the cooler air of the trunk space may flow out into the open as a diurnal forest wind. L. Herr (*80*) and also K. Dörffel (*663*) have demonstrated it by means of the cooling and moistening of the air which it brings out. In its origin it is very similar to the sea breeze which during the day blows from the cool sea in over the hot land. Even in 1920 A. Schmauss (*681*) mentioned "Sea Breezes without a Sea."

There have as yet been no observations of a nocturnal country wind corresponding to the land breeze and filling the counter part of the diurnal forest wind. The braking action of the stand hardly lets such a wind develop. On the other hand there arises a nocturnal forest wind representing an overflow of cold air from the crown surface out over the surrounding open country. It has been studied and well described by H. G. Koch (*670*, *670*a) with the help of rubber balloons. On the level it attains a speed of only 1 m per sec. It is noticeably stronger on a mountain slope, where the upper part is forested. The cold air near the crowns then flows down-grade at speeds of as much as 3 m per sec and sinks to the open ground at the border of the stand. The hunter on a lofty post dislikes this nocturnal forest wind because it carries his scent to the wild life outside.

Seed distribution at the margin of the stand, which is strongly influenced by wind and by convection was carefully investigated by H. Hesselman (*669*) in the Swedish province of Västerbotten. In the midst of a 90 year old 18 m pine stand at Lund, situated in a bare cutting 100 by 200 m, 262 seed boxes of ¼ sq m area were constructed flush with the ground. The seed yield of the winter of 1936–37 was distributed as follows over the various zones near the stand:

TABLE 60

Distance of seed boxes from edge of stand	Seeds caught: Number per sqm	Number %	Weight g	of seed wings: Length (mm)	Width (mm)
In inner edge 37 m	105	144	3.8	12.9	4.2
22 m	89	122	3.6	12.7	4.1
Both sides of stand margin	73	= 100	3.6	12.9	4.2
In outer edge 7.5 m	52	71	3.4	13.1	4.0
22 m	29	40	3.4	12.8	4.2
37 m	17	23	2.9	13.0	4.2

The decrease in number of seeds with distance from the edge of the stand was steady and in good agreement with the theory of Wilh. Schmidt (*113*) based on the law of convection. (Chapt. 4.) The size of the seed wings makes no difference, for the last two columns of the table show the same average size, but the light seeds are, on the average, carried further than the heavy ones. The light ones, however, are also the bad ones. While at the edge of the stand only 7% of the seeds were hollow shells, the percentage at a distance of 37 m was 19%.

A true transition phenomenon which occurs only at the border of the stand, is fog precipitation. When wind-blown air carries water droplets, as happens particularly with mist in the higher parts of the mountains, the droplets are caught by the twigs, leaves and needles on the side of the forest which is exposed to the wind. They fall to the ground as additional precipitation. P. Descombes (*661*) calls this "occult precipitation," R. Süring (according to *674*), "horizontal precipitation." We prefer the designation "fog precipitation" as used by K. Rubner (*678*).

Table Mountain at Capetown is known for the so-called tablecloth which results from the driving fog which forms on the windward side of the mountain and dissipates again on the lee side. When Marloth (*675*) placed two rain gauges — the one in normal location, the other covered with a bundle of twigs, the latter, after two months of observations had caught 16 times as much as the open gauge. P. Descombes and others drew some bold conclusions from this as to the amount of water gained by the forest through fog precipitation. The effect is however limited to heights where fogs are prevalent and it is always a forest margin phenomenon.

F. Linke (*673*, *674*) has made some measurements in spruce stands in Taunus at 800 m above sea level. In the years 1915–19 he found the following excess of the rain gauge located in the forest over the one in the open.

TABLE 61

Rain gauge	Month: Least fog (June)	Month: Most fog (Nov.)	Summer	Winter	Year
Directly at forest edge	104	301	131	184	157
Farther into forest	87	259	90	159	123
Average number of fog — days	11	24	14	22	18

The excess therefore reaches very high values. It decreases considerably as soon as we move into the forest from the margin.

K. Rubner (*678*, *679*) constructed a special gauge for the measurement of fog precipitation and used it in a six year series of measurements at the Erzgebirge at 745 m. According to his findings, Linke's figures are to be considered as upper limits for our German conditions. His investigation also shows, however, that fog precipitation may be of considerable importance in the water economy of the stand zone near the edge of the forest.

A similar transition phenomenon exists with the dust content of the air. The forest filters out the dust which exists in abundance above the open land. Sometimes, we can recognize this effect from the dust cover of the trees on the forest border in the vicinity of very dusty roads. M. Rötschke (*256a*) investigated this process under normal conditions and found in the case of wind perpendicular to the stand a strong maximum of dust content at the inner border, and in the case of wind diagonal to the border of the stand a great increase at the outer border. For the first case a numerical example may be mentioned which is chosen for a 12 m high stand of firs, pruned up to 2 m. The wind above the open land was at the time of observation (Jan. 29, 1935) 2–3 m/sec. the temperature at the ground, lightly covered with snow, was $-2°C$. At the surface of the ground, there were:

10100	10200	10300	14000	11800	1500 dust particles
100m	50m	25m outside,	25m	50m	100m inside the stand,

per liter of air. The interior of the stand then becomes more and more free of dust, a fact considered as one of the advantages of the air in the interior of the woods.

The subjects thus far considered have given us some idea of how many factors determine the climate of the forest margin. Both the inner and outer edges possess a habitat climate with special, well developed characteristics. The practical forester has long reckoned with them. C. Wagner (*682*) especially, in his book "The Fundamentals of Spatial Arrangement in the Forest," has based the method of screen cuttings from the north edge predominantly on the stand climate. He has derived the climates of the different stand borders from only two factors — i.e. direct insolation and the rain falling obliquely from the west — obtaining excellent results by this method.

It is regrettable that there are no measurements, no actual data, on the climates of stand margins. We do not know today what is the

average amount of precipitation at the different margins nor how heavy rains and light snow which is easily drifted by wind and turbulent air, differ in this respect. We do not know the original distribution of dew as it forms, nor whether the early removal of dew at the borders which get the early morning sun is alone responsible for the different benefit derived therefrom. Whether the same stand border is warmest at all seasons or whether there is a seasonal displacement; whether the driest border always coincides with the warmest, the wettest with the coolest; whether ground temperatures and dryness are always parallel with the climate near the ground or whether this relationship is disturbed by the macroclimate; how all the elements mentioned vary in the realms of the inner and outer margins — all this is of direct significance to the living conditions of the young growth, but we have no observational data thereon.

If it be asked, why this is true, we must answer first that the task of evaluating a habitat climate in figures is a tedious and difficult one. All observations are complicated by accidental weather conditions. The constant, significant features of the habitat climate must be sifted out. The forest manager usually has neither the time nor opportunity to make observations or interpret them. But this is not the only reason. Rather, the problem itself is too complicated. Not only season and weather, but also the kinds of wood, treatment of the stand, condition of the soil and topography — all result in continually varying data. No one can expect to achieve more than purely local results from first measurements of this kind.

R. Geiger has very recently shown (667) that a great circular hole cutting offers, along its inner margins the best possibility for this type of research. The uniform air body resting above the cutting and in no way of different effect, microclimatically, by reason of outer influences, is altered in respect to habitat only at the edges of the stand. This alteration, according to observations during the summer of 1940, is so great that it can be measured without great technical difficulty. There is thus a possibility of solving the fundamental questions concerning the climate of forest margins in a systematic way.

SECTION VII

THE RELATION OF ANIMATE CREATURES AND MAN TO THE MICROCLIMATE

CHAPTER 36

The Animate World and the Microclimate

The microclimate is an effective habitat factor for stationary plants. This is the information we were able to derive from Section VI. Now we shall go a step further and take up the relations between the animate world and the microclimate.

For animals also, the microclimate is very important. Although they have in general, the ability to change their habitat, which plants lack, they are nevertheless subject to the influences of the microclimate to a large extent. This is particularly true of creatures which move slowly, if at all — such as larvae, worms, beetles, caterpillars, etc. But there are many large creatures as well of a "fixed habitat" as W. Kühnelt (*697*) expresses it. Yes, even the swift whose flights in the upper airlayers always arouse our wonder, has to return at night to its home whose habitability depends on the microclimate.

H. Grimm (*692*) has attempted a general answer to the question whether microclimatic research is as essential to zoology as it is to botany. His answer is an emphatic "Yes."

"Animal geography," he says, "should be based, in its form, on microclimatic considerations. The range of any kind of animal breaks up along its borders into island-like occurrences. Just as in the distribution of plants, animals in an unfavorable macroclimate can exist only in microclimatically favorable places. The egg and larva of the hook worm, for example, which are adapted to tropical temperatures, in our country find the conditions of their native climate in tunnels and mountain gorges where they prosper very well, to the discomfiture of mountain workers. The rat flea, which carries the plague, flourishes in the underground heating plants of Paris, although he is a guest from warmer lands. E. Martini and E. Teubner (*702*) proved, through laboratory experiments and observations in the open, that the true malaria mosquito (Anopheles) makes different demands on the microclimate from other mosqui-

toes. This has a direct bearing on the danger of malaria for men in the tropics, for the microclimate of tropical residences, including stables and other buildings, determines which kind of mosquito is suited or not for living with man. Many such examples can be cited.

It is necessary, therefore, in a textbook of microclimatology, to consider also the relations of the microclimate to the animate world.

In describing the relations between the plant world and the microclimate, we began in Chapter 26 with the heat economy of plants. The animal has its own heat economy as well, but through the more numerous and advanced life processes which distinguish animal from plant, some difficult physiological questions are involved in addition to the outside factors in the heat economy of the animal body. We need only remember the warm blooded animals. It is neither possible nor necessary to take up these questions here. We shall confine ourselves to a study of the microclimate as an environmental factor for the animals.

Attention is first directed to the dependence of the life and growth of the animal world on the microclimate.

While describing in Chapter 22 the influence of different sun exposures, we mentioned the investigations of E. Schimitschek (706) on the bark beetle. The scarcely moving larvae of this kind of animal developed or died on one and the same tree-trunk according to the temperature conditions of the bark climate. According to W. Kühnelt (697) the physical properties of the soil (compare Chapter 14) — its heat conductivity and water permeability — are responsible for the appearance of certain kinds of animals. Animals which especially need heat consequently press farther northward on sandy soils. For example, the Mediterranean locust (Stenobothius Fischeri) as far as the sand dunes of lower Austria.

In connection with Fig. 89, we have already described the marked microclimatic differences in the special observation network at Lunz in their effect on the plant world. The animal world, too, is conditioned by the same habitat conditions, as E. Schimitschek (706) had demonstrated.

The pine-bud roller (Evetria turionana Hb.) is often seen as low as the saddle of the sink-hole, whose significance in the temperature stratification within the sink hole has been mentioned in Chapter 18, Ten meters below the saddle it is very rare indeed, while 30 m still lower it occurs only sporadically, since most of the caterpillars have died. A true bark beetle (Pityogenes conjunctus Reitt.) occurred in the dying and dead knee pine twigs of the sink hole. "On July 19, (thus Schimitschek describes the conditions in the cold ground

of the sink hole) the eggs of all broods studied were laid; in only a few rare instances there were some newly hatched larvae. Besides this freshly laid brood there were,—not counting the brood just hatched and in some cases still harboring young beetles—also some broods with larvae three quarters grown. On Sept. 23rd the larvae of the July brood were half grown—part of them gone. Late laid eggs do not survive the larval stage here but die off. The generation here is biennial; in the most favorable cases, of a 1½ year term. On the highest slopes of the sink hole, an annual generation could be proved without exception. The frequency of occurrence of Pityogenes conj. increases from below upward! The number in the brood at the upper edge of the sink hole is greater than that at the bottom of the sink hole."

H. Franz (*691*), in a similar instance, showed the distribution of various kinds of beetles in a valley at Parndorf (southeast of Vienna). In the meadows of the moist valley bottom there are different kinds from those on the dry slopes or on the higher pastures.

It therefore appears that certain kinds of animals can serve as identification for a definite microclimate to which they are confined. Insects are the best climate indicators of all. W. Kühnelt (*697*) has proposed the term "bioclimatic index forms." In the realm of the microclimate they permit a classification on the basis of animals, much as in the macroclimate W. Köppen's "beech climate" is identified with a plant. According to H. Grimm (*692*), J. H. Blake, in a quantitative study of forest insects, has differentiated four definite zones between elevations of 0.15 and 11.00 m. M. Klemm subdivided the growth of a meadow floor into six zones on the basis of animate inhabitants—i. e. the geobium, with angleworms, beetle larvae and butterfly pupae; the herpetobium, with beetles, spiders and ants; the bryobium with mites and spring tails (collembolae); the phyllobium with orthopters, aphids and caterpillars; the anthobium with all flower visitors; and finally the aerobium with the libellae. Each of these six zones is characterized by a definite microclimate and by certain kinds of creature.

As plants and their habitats are closely bound together, so are animals and *their* habitats. It is possible, however, for animals as well as plants to exist in unfavorable circumstances. As protection against too great heat they have heightened transpiration; against the danger of dryness the animal has a number of weapons which W. Kühnelt (*698*) has summarized. But in addition the animal has a fundamentally different possibility, which we have already mentioned—that of motion—change of environment. While an un-

favorable microclimate represents for plants an "inescapable environmental condition," to use an expression of W. Hausmann (*736*), an animal can, to a greater or less degree, get away from it.

Lizards avoid harmful overheating by seeking cooler, shadier places. The spotted lizard (Uma notata), according to W. Mosauer (*703*) endures the enormously high noon-time temperatures in open desert sands by elevating its body from the ground as it runs rapidly about. Pools which are drying up are forsaken by salamanders and other inhabitants; this usually occurs at night, when moisture conditions are most favorable. Dancing mosquitoes, as F. Lauscher (*699*) accidentally observed, in a brisk wind which blew part of the time up-valley and part of the time down, always sought shelter in the lee of a hedge. According to F. S. Bodenheimer (*686*) a swarm of African migratory locusts take a position at midday such that the main axis of their bodies is paralleled to the sun's rays, thus absorbing as little heat as possible.

But animals do not use their faculty of movement merely to escape an unfavorable microclimate; they also seek out a favorable one. These same migratory locusts, which at noon all protect themselves from the heat, in the morning all present their broadside to the insolation in order to enjoy the early morning sun. Anyone who keeps chickens may from them too learn microclimatology at unpleasant seasons, for they are wonderfully wise in choosing the most comfortable place in all the range accessible to them at any moment and for any given weather.

I found a fine observation of H. Wiele's (*711*) in the description of his experiences while hunting animals for Hagenbeck in the Himalayas. In the month of April, before the trees were in leaf, a great swarm of locusts appeared in the neighborhood of Rawalpindi. A heavy thunder storm in the night and the consequent temperature drop had evidently exhausted the creatures exceedingly, for they remained motionless as soon as they landed. The author thus describes his journey through the swarm. "When we had traversed the dense nucleus of the flight and were again walking in the bright sunlight, we found that the beautifully smooth-rolled country road, covered with bright grayish blue, crushed granite, was so thickly covered with locusts that it appeared to be overlain with a thick, loosely-woven, shrieking bright-green carpet, on which the shadows of the tree skeletons with their thousand-fold ramifications stood out sharply as a design in a pale gray color tone. For ***not a single insect sat in the shadow pattern.***"

According to the observations of E. T. Nielsen (*705*), the leaf

locust (Tettigonia viridissima) in Denmark begins its song in the afternoon, sitting meanwhile on low growths, such as weeds or reeds. Then in the evening they are heard singing up in the trees. In order to determine whether the latter were different locusts, or whether the same ones which had been singing below climbed up as darkness came on, he tied several meters of thread to some test animals. The locusts which were first singing on the ground did indeed climb spirally up the trees when the ground air began to cool. E. T. Nielsen assumes that they seek more comfortable temperatures at higher levels.

I have occasionally been able to observe in an old pine stand how in the early morning hours the insects seek the warm air layer which the rays of the morning sun spreads over the tree tops while cool, moist night air still fills the trunk space. Thousands upon thousands of hovering flies, mosquitoes and butterflies assemble there — a plethora of life, whose existence in such masses seems scarcely credible. The living cloud was so sharply defined at its lower boundary by microclimatic limits that to one climbing up the observation ladder it seemed like sticking his head through a boundary surface.

The examples just cited have shown that animals understand how to avoid the unfavorable microclimate in their life customs and how to seek the favorable. They also often exercise astonishing prudence in the location of their dwellings.

The great nest of the forest ant is really nothing but a miniature testing ground for demonstration of different exposure climates in all directions. The construction of the nest of poorly conducting materials, such as evergreen needles or litter, makes the differences very distinct. G. Wellenstein (*710*), in September 1927, made numerous temperature measurements within the Trier district on the nest of the red forest ant (formica rufa L.) As an example there are observations on a nest 80 cm high and over 12 m in circumference which stood under young spruces on a steep slope. Although the weather was cloudy and rainy on the observation days of Sept. 13–15, 1927, the following temperatures were found, here arranged according to time of day:

Hour of day		3 A.M.	9 A.M.	5 P.M.	9 P.M.
Air temp. above the nest		8	11	10	12°C
Nest temp.	shady	12	14	13	16°C
at depth of 25 cm.	sunny	21	22	18	22°C

The nest at a point 25 cm below the surface on the shady side was 3° to 4° warmer than the surrounding air, and on the sunny side 5°

to 9° warmer than on the shady side. The design of the nest is of such a form that the different microclimates can be utilized by the animals. A. Steiner (*708*) describes the design and construction of the nest as follows (here somewhat abbreviated). "On the southern side, protected from the wind, there is a dome shaped structure made of earth and vegetable material, and filled with numerous air spaces. The form of the dome which changes purposefully from hemisphere to cone according to insolation and precipitation conditions serves as heat collector. It reaches its relatively greatest effectiveness in this respect at lower solar positions; thus a mathematical calculation shows that for latitude 47° a hemispherical dome at noon on Dec. 21st receives twice as much insolation as does a horizontal surface, at the equinoxes $1\frac{1}{4}$ as much and on June 21st, 1.05 as much. In addition to increasing heat absorption there are also means for reducing heat loss, in particular the thick dome roof of vegetable material — a poor heat conductor — the inner insulating air chambers, and the nightly closing of the nest openings. By these means, the temperature in the center of the nest, which is at an average depth of 30 cm, often remains for a long time in summer between 23 and 29°, which is 10° above the corresponding ground temperature. The temperatures in the upper part of the dome where conditions vary from place to place with the position of the sun, are used to best advantage by tireless shifting of the brood. In a similar manner the brood is protected from overheating, by moving it into lower portions of the nest."

Tropical termites, on the other hand, have to protect themselves against excessive insolation. Fig. 170 shows, according to R. Hesse (*694*) a termite nest from Arnhemsland in North Australia. As the right hand half of the illustration shows, the structure as viewed from the noon side is extraordinarily narrow and pointed. If, however, it is seen from the west or east (left hand view), it appears extended. These compass nests of termites are the counterpart of the compass plants mentioned in Chapter 22. They are the termites' method of protecting themselves against insolation which at lat 11° is all too strong. The earthen galleries which the termites build along their roads are also, according to W. Kühnelt (*698*), to be considered as protective measures against too great evaporation.

The entrances to rabbit burrows in the sand dunes along the North Seas coast are often placed very efficiently. On the island of Sylt, for example, I saw such an entrance situated on the mid slope of a sand dune so that the accumulated water of a heavy rain could not enter. Overhanging clumps of heath weeds protected it like an

awning from rain and dropping water. The exposure was southerly so that the entrance received plenty of sun and no north wind could blow into the burrow. A huge thicket on the west afforded additional protection against a storm from that direction.

H. Löhrl (700) reports concerning the bats (nyctalus noctula Schreb) that in their wide range they are astonishingly skillful in selecting a place with the warmest microclimate for hiberna-

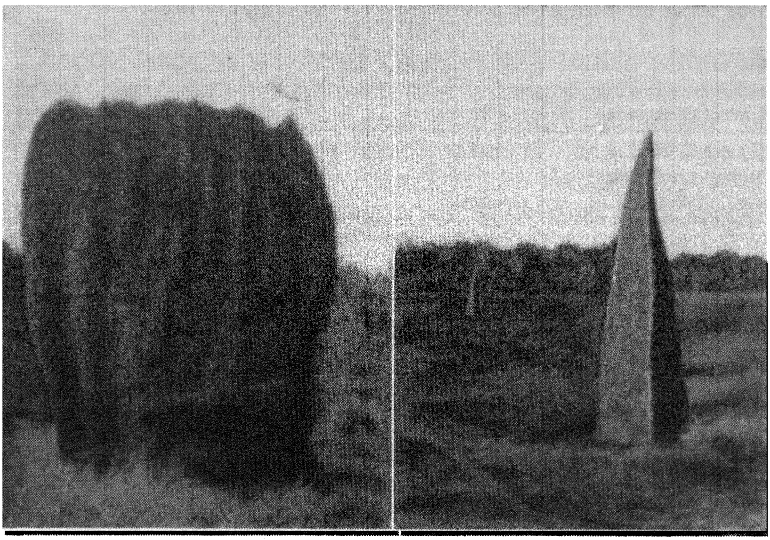

FIG. 170. Compass nest of a species of termite in North Australia. (After R. Hesse)

tion. The animals observed in Munich selected (as they often do) a plaza in the great city where in winter it is warmer than in the country, choosing moreover in the warmest part of the city an inside facing house corner which opened toward the southeast. 12 m above the street — high above the cold ground air layer — the animals took over two holes, some 50 cm deep, in the wall behind the eaves where they were protected from rain. The inside of the house was heated and one of the main steam-pipes leading to the bedrooms ran past the nest. The following simultaneous temperature measurements were made: at the outside meteorological station, $-14°$; on the roof of the building, $-5°$; at the hibernation quarters, about $0°$!

In the choice of favorable microclimate by communal animals, warming by bodily heat is a factor. A. Himmer (695) has shown

that the heat regulating mechanism of the community is better the higher and narrower is the optimum temperature range for the development of the brood. A nest of Vespa vulgaris between July 24 and October 5 was, on the average, 16.4° warmer than the outside temperature, a beehive, 12.3° warmer. E. T. Nielsen (*704*), in the summer of 1937, made comparative thermoelectric temperature measurements in an empty nesting box, in a second in which bumble bees had made their nest, and in the open air nearby. For the 14 hour term he found the following average temperatures:

TABLE 62

Time of Observation	Free Air	Empty	With bumblebees
July 9th–26th	18.6	20.2	30.6
August 12th–27th	19.6	20.9	24.2
Aug. 29–Sept. 1	17.3	17.9	18.6

In the first period, since the nest was fully occupied, the bumblebees produced 10° excess temperature; in the evening 9 P.M., as much as 13°. This excess gradually diminished; toward the end of August there were only a few bees left and they were killed on the 29th. At once the temperature differential fell to less than 1°.

In conclusion special reference should be made to forest entomology. It is known that injurious forest insects are ever present. They become a real danger to the stand only when the normal biological equilibrium is disturbed and a great multiplication of the harmful insects takes place. The weather plays a great part, for the development of egg, larva, pupa, and butterfly depends at every stage on temperature and moisture conditions which can be studied in the laboratory. Mass increase, as is known today, presupposes the accidental coincidence of favorable meteorological conditions in successive years. Naturally it is not the macroclimate which makes the difference, but the microclimate which the caterpillars experience on the twigs and needles in the treetops. In the more recent battles against such outbreaks of forest insects, habitat measurements have been carried out in the tree tops of the stand in question. More along this line than can be discussed here, will be found in the writings of H. Eidmann (*688*), K. Escherich (*689*) and W. Zwölfer (*713*). In dusting poisons by airplane, microclimatic considerations have been necessary to assure success. This was mentioned at the end of Chapter 4.

CHAPTER 37

The Unintentional Effect of Man on the Microclimate

When we attempt to survey the relations of man to the microclimate the first thing that strikes us is that man like the other animals avoids unfavorable habitat and seeks the favorable. This is, as with beasts, an instinctive procedure at first.

Anyone who has to wait in the street in a cutting winter east wind, forsakes the stormy corner and seeks a calm microclimate. When the first warm days of spring arrive in the large cities the mothers with their baby-carriages instinctively find the sunniest, warmest, and most sheltered microclimate in the city. In summer we find those, both on the beaches and in the mountains, who are true artists in the discovery of comfortable places to lie and sit. I once read of the homeless of London, who spend their nights on Victoria quay, that they learn accurately the temperature of every house wall and seek particularly the outer walls of hotel kitchens.

With increasing civilization man loses such sensitivity to the microclimate. Only at a later stage of development is there a conscious process of a rational search for the best microclimate, as we may say in imitation of W. Hellpach's (737) "rational selection of climate."

Obviously it is the consciousness of purpose which differentiates the relations between man and his microclimate from those between other animals and theirs. But we shall not speak of that at present. Long before the idea of a microclimate had taken form, and before there was any research into microclimatic laws, man as master of nature exerted a powerful influence on the formation and dissolution of microclimates.

These unpremeditated effects we shall consider in this chapter. The first fact to meet the eye is that man is a great disturber of microclimates.

Unmolested nature, which reveals the rich diversity of creation, possesses an enormous number of microclimates. They exist close together in harmonious contrast. Man's measures of culture, however, show the monotony and poverty of purposeful, reasoned action. This appears in almost all the factors which determine the microclimate.

Agriculture has shown a preference for some few plants which

have proved most profitable. With the reduction in number of varieties there has been a standardization in structure of the plant communities. It is only necessary to look at the uniform fields surrounding a city. The climate near the ground has become a unified climate.

In forestry the most profitable kind of wood — in Germany, spruce — has been planted exclusively to an increasing extent, often in militarily directed plantations. In place of the natural mixed forest with its variegated mixture of different microclimates has come the more profitable but monotonous artificial forest. Only very recently have great calamities and a new understanding of biological harmony in the forest paved the way for a change.

A similar development is observable in a few advanced countries. The destruction of forests as a result of excessive lumbering has worked out in a roundabout way, through changed soil and microclimatic relationships, to affect the macroclimatic condition of the country in question. There is no lack of warning examples. H. Scaëtta (*761*) on the basis of his experiences in central Africa, says that the burning of undergrowth practiced by the natives is "the great destroyer of the original microclimate." The plant cover used to modify in a thousand different ways the transition from the ground climate, which, under a tropical sun is extreme and inimical to vegetation, to the climate of the free atmosphere — thus giving a chance for life to very different biological communities. When the plant cover fell a victim to fire, the unfavorable microclimate alone returned to control over the bare ground.

How this impoverishment of vegetation and microclimate go hand in hand may be seen by a single example from a botanical microclimatic study by K. Hummel (739). In the Rotach valley in Allgäu, which, at a height of over 500 m, possesses a harsh climate, decidedly heatloving plants of a predominantly southern range occur on the uncultivated south and southwest slopes. Among these are Cotoneaster tomentosa, Epipactis rubiginosa, Cephalenthera rubra, Orchis purpurea, etc. Temperature measurements of these habitats showed an extremely warm microclimate with summer temperatures up to 70° on the ground and up to 45° in the air close to the ground.

The increasing opening of the Rotach valley has the effect of the establishment of pasture areas in place of the original mixed forest in this neighborhood as a concession to the needs of the dairy industry. There are also cultivated forests with uniform close crowns. Heatloving plants will soon find no place of refuge afforded them

by that microclimate in which alone they are able to bloom and bear fruit consistently. The time is in sight when they must disappear entirely.

In addition to the impoverishment of the plant world there is an equalization of ground conditions. It was pointed out in Section IV how kind and condition of soil work out in the ground climate. The increasingly technical cultivation of the soil tends to its increasingly more perfect mixture. Moist meadows are dried up; waste land is turned into meadows, useless thickets and woods are removed. From south Mähren, for example, F. Koláček (742) reports that about 1700 A.D. a total of 85 square kilometers (i. e. 3.4%) of the country was occupied by ponds; today that area has been reduced to 0.1%.

But the labor of man does not always lead to destruction of the microclimate. He also establishes new microclimates, especially through his building activities.

Every newly built dwelling makes a number of separate climates out of the single one preexisting near the ground above the building site. On the south wall the microclimate will be so favorable that good fruit, perhaps even grapes, can be grown. This gain is at the expense of the north side, which is dark, cold, damp and raw. Still different are the east and west sides. The climates of the various rooms are modifications of these four outdoor climates. In addition there is the cellar climate and the attic climate.

Where a nucleus of buildings is formed, there will be in time a special city climate. It differs so decidedly from open country climate and has such great significance for the civilized man of today that we must devote the next chapter to its treatment.

In industrial regions, finally, there ensues a landscape where the slope and drainage of the ground are the only remaining features in common with the original natural conditions. But in its new form it too is rich in microclimates of the most varied sorts. Refuse dumps afford new slope climates. The lifeless underground of huge track areas creates a very hot microclimate near the ground. Where a road embankment intersects the country slope climates are formed; they can make cold air dams which may cause floods of cold air. Interference with soil drainage has its reaction on the microclimate. The reader can fill in the rest of the picture from his own experiences.

The unintentional disturbance of manifold microclimates on the one hand, and the establishment of new ones on the other, has been

recognized by man only by the real, practical damage resulting therefrom.

Leveling off the landscape lessens the inequalities of the surface. (See Chapter 28). The wind, which is always blowing strongly in the upper air, can therefore more quickly and more strongly affect the ground surface. Increasing the velocity of the wind close to the ground may raise dust if the soil be light and the weather dry. There will be dust storms. The soil which is borne away takes sown seed with it. Plant roots are laid bare so that they die, or they may be buried and choked. The sum of small effects is great damage.

In the dry areas of the western United States the wide open spaces have favored extensive use of tractor plows. They are most efficient on broad flat plains. As a result of the combination of topography and method of cultivation came dust storms. The reaction today threatens to become catastrophic since a diminution of rainfall in consequence of a change in the macroclimate still further strengthens the disturbance of the microclimate.

The danger of erosion is not absent from us either. According to H. Schwarz (762) there is at Vienna, in northern Marchfeld, about 5,000 hectares, in the southern Vienna basin about 11,000 hectares, of erosional land. The drainage of sour meadows and clearing of forests is said to be the cause of dust formation here.

The establishment of new climates has proved especially advantageous in cities and industrial areas. Here are possibilities for improved health which command attention. We return to this in the following chapter.

CHAPTER 38

The City Climate

There are two methods of determining the influence of a city on its climate. Plenty of material is afforded by the records of many observation stations which are situated partly inside and partly outside the city. From a comparison of a series of observations the characteristics of the city climate can be determined in relation to time of day, season and weather. In order to estimate climatic changes in large, growing cities it is necessary to have many years' series of undisturbed observations from such stations as a basis.

Since such comparable stations are rare and since experimental observations often give valid conclusions, Wilh. Schmidt in Vienna and A. Peppler in Karlsruhe, almost simultaneously, in the year 1929, made use of a new method which was soon accepted with general approval and found application in most great cities. It is the method of temperature-measuring journeys. Temperature measuring equipment, usually electrical, is installed in a motor car, free from influence of the motor, and records are made during the journey. By traversing, allowance is made for frequent return to the same point of the field in order to screen out the influence of temporary temperature changes. A bicycle with a mercury thermometer on the steering post is useful when needed.

Recently, in addition to temperature, similar measurements have been made of atmospheric humidity, solar and sky radiation, the dust content of the air, etc. The motor car must have the necessary equipment and as a "research auto" becomes a moving laboratory. Wilh. Schmidt in Vienna was the first to use such an outfit. It naturally finds application in microclimatological research far beyond the limits of city climates.

In 1937 the results of city climate research were assembled and presented by A. Kratzer (*781*). His comprehensive book should be in the hands of everyone who wishes to go into the question thoroughly. In the following survey I have tried first of all to mention publications which have recently appeared; in the literature on the present chapter, only those works not appearing in Kratzer's 250 titles have been listed.

In Germany a third of the inhabitants live in large cities; two thirds, in places of over 2000 inhabitants. In the whole world almost

10% of all the people are included in 540 large cities. There is probably no other microclimate which has so far-reaching an effect on mankind, therefore, as that of the city.

In cities great quantities of coal are burned by industry and in household heating. This means an artificial input of heat and a pollution of the air. The influx of heat is the easiest of all causes to understand in its influence on the city climate; it effects a rise of the city temperature in comparison with that of the surroundings. The question is whether the increase of heat is important enough on the whole to play a part in the heat balance.

According to A. Kratzer we can assume that in large German cities there is received an average of 15 to 30 calories per day per sq cm throughout the year, according to the known consumption of coal. With this we compare the results of the Karlsruhe radiation records. The addition of heat from direct insolation and sky radiation amounted to 52 cal per day per sq cm of level ground as a December average; in June this figure was 518 cal per day. The amount of artificial heat is therefore by no means negligible. In winter, while it is above the yearly average, it helps out the natural heat furnished by the sun. It is somewhat different with the effect of this additional heat on temperature, for while the irradiation from sun and sky affects not only the city areas but the surroundings as well, the artificial heat is limited to the city. Thence it is carried away upward and outward with a speed proportional to the amount of air movement.

The *pollution* of city air is very important. In London there is an average deposit of 12 g per day per sq meter. For the industrial area of Rochdale (near Manchester) the amount is twice as much. The total amount of soot which falls on the county of London in one minute can scarcely be carried away by a strong man. To these excreta of industry there is to be added the train smoke, insofar as coal is burned, and the dust which street traffic continually stirs up.

In measuring the dust content of air, the best means we have today is the Zeiss conimeter. H. Herrig (*776*) carried out some measurements in 1936 at Marburg on the Lahn. The city of Leipzig was carefully studied by A. Löbner (*784*). According to him, three dust layers, one above the other, can be recognized in a great city. The lowest, which lies between houses and on open spaces is caused by street traffic and railway smoke. A second layer which is fed by chimneys lies above the houses, about 20 m from the ground. Above this, at a height of from 50 to 60 m, is a third, which is caused

principally by factory chimneys. The two upper dust layers increase the dust in the street air only when there is rain and fog.

The study of dust distribution with different wind directions permits the location of centers of dust distribution and recognition of the purifying action which narrow green areas already have evidenced. Fig. 171 shows the lines of equal dust content per liter of

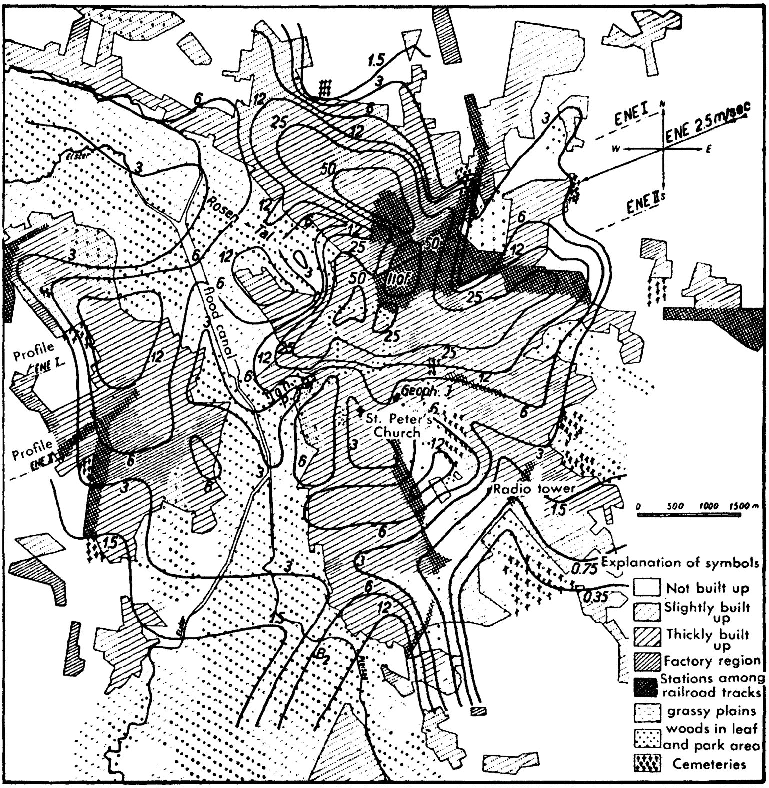

FIG. 171. Dust distribution in the city of Leipzig with east north east wind. (After A. Löbner)

air on a day with ENE wind, the recorded figures to be multiplied by 100. The air extending above land without buildings has a small dust content and is immediately enriched with dust as we enter the city of Leipzig. In the depot district in the NE part of the city this enrichment is very sudden and strong. The green areas of

Rosental as sketched on the map filter the dust out again just as quickly. As we pass through the air of the industrial district to the west, its dust content increases only slightly, which probably indicates that the high chimneys throw out only the highest dust layer — not that near the ground, in which the measurements were made.

As a whole, Fig. 171 shows clearly the growth of air pollution with the enlargement of built-up town areas. How important such dust content measurements are in the estimation of state hygiene scarcely needs emphasis. According to A. Löbner's proposal, the hygienic status of a city in reference to its dustiness should be defined and determined by such measurements.

To the stranger the great dome of haze which hovers over a large city and covers it like a flat black bowl in fine calm winter weather, appears as remarkably characteristic. "Outside," as A. Kratzer clearly expresses it, "the blue sky laughs over the landscape, while in the city all is covered with gray and the sun shines only with a weak yellowish-red light. Outside it is possible to see church towers several kilometers away; inside, the houses on long streets soon disappear in impenetrable gray. The larger the city, the denser, heavier and more resistant is its haze hood."

This haze hood absorbs a notable amount of sun and sky radiation; when incoming radiation prevails, as is the case at noontime and in the summer, it intercepts part of the heat. Consequently the haze hood attains a temperature higher than that of the surrounding air at the same level. The result is that the ground air of the city, which stands to lose this part of the insolation, is cooler than the surrounding ground air. The midday temperature maximum in the city, as shown by measurements, is as much as 0.5° lower than outside the city.

In our climate (Germany), however, where outgoing radiation prevails the greater part of the time, the protection against net loss of radiation afforded by the haze dome is much more effective. At night, and especially in winter, therefore, a large city is warmer than the country. The effect is intensified by the already mentioned artificial heating by numerous fires which are more numerous than ever at times of prevailingly outward radiation. The lowest temperature of the day in the city is consequently 1 to 2° higher than outside the city. As the city grows, the daily temperature minimum considered absolutely, grows also. Recently H. Arakawa (772) determined for Osaka a rise of 2.6° in a century; for Tokio, 1.5°.

From these premises it follows that the diurnal range of the city temperature is restricted in comparison with the temperature of the

surrounding country, the higher minimum having more to do with this than does the lower maximum. The great amount of masonry in a large city acts in the same direction, warming up slowly and also cooling off slowly. As a result the city lags behind in the general morning warm-up. On the other hand the streets hold the heat in the evening, especially in midsummer. Fig. 172 shows the temperature distribution of a July evening in Karlsruhe. In the center of

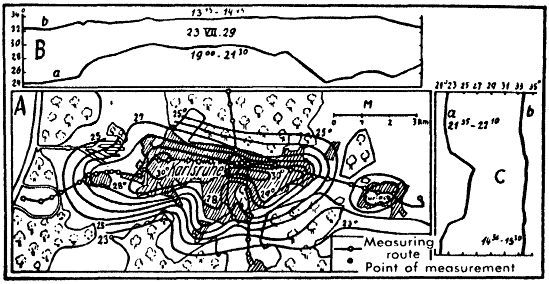

FIG. 172. Temperature distribution in the urban area of the city of Karlsruhe on a hot summer evening. (After A. Peppler (From A. Kratzer: Das Stadtklima))

the city it is as much as 7° warmer than in the open country, as is clearly shown by the course of the isotherms and by the temperature cross-section shown at the side. During the first half of the night the evening cooling process proceeds very gradually from the outlying portions of the city toward the middle.

H. K. Metzler (786) was able to establish this phenomenon for humidity as well, by a series of measurements in Hannover. On the clear nights of Sept. 18–19, 1934, the maximum relative humidity at the airport near the city occurred at 10 P.M. In the suburbs the time of maximum was 2 A.M., and, in the interior of the city, not until 6 A.M. Moreover, these succeeding maxima were about 10% lower respectively. Hence, the city area is dry in comparison with open country. This is especially true of summer evenings, when a difference of 30% has been measured in Munich between the center of the city and the English Garden. It holds however throughout the day. Consequently cities are about 5% drier than the country. This is readily explained by the lack of evaporating surfaces (with the exception of grass plots) and the speedy removal of precipitation into the sewers.

When, with relatively calm weather at midday in the summer, the city is warmer than its surroundings, it is able to set up its own

peculiar circulation system. Just as the air streams into an open fire from all sides,[1] a light wind blows toward the center of the city from all sides. It brings fresh air from the outer areas, at the same time raising and dividing the haze hood. Cumulus clouds can form in the rising airstream, rich in condensation nuclei, just as they often do above great fires.

H. Mrose (*788*) has recently pointed out the need for paying more attention than has hitherto been given, to the influence of winds having their origin in microclimatic conditions such as have been described in Part V.

In spite of its drier air, the city has more fog than the country. Dust and the combustion products of coal furnish such a rich supply of condensation nuclei that, for a correspondingly similar state of readiness of the atmosphere for condensation, the formation of fog droplets begins first in city areas. Fog is often observed first, or at its densest, in the neighborhood of smoke-enveloped railway stations. The growth of cities has consequently led to a noticeable increase in fogginess. B. Hrudička (*777*) has recently published the number of days on which fog occurred at Prague, according to many years of homogeneous observations at the astronomical observatory in that city. For 20-year intervals since 1800 the average annual number of foggy days is

1800–1820	1820–1840	1840–1860	1860–1880	1880–1900	1900–1920
83	80	87	79	158	217

The effect of industrialization since the middle of the past century is clearly evident. Here and in other places this increase has recently ceased. On the contrary the relationship is becoming more favorable, in spite of continued city growth. The explanation lies in more perfect combustion of coal through better designed furnaces and in the introduction of electric railway equipment.

The tendency of city air toward condensation, together with the upward movement of the air over the center of the city can have an influence on precipitation. Fig. 173 shows lines of equal precipita-

[1] The following little experience may be mentioned here: — On Saturday, June 6, 1931, I was awakened about 3:45 A.M. at my home, 11 Arcis St., Munich, by the howling of the wind. The weather forecast had been for a clear sky with no winds; so I hurried to the window to have a look at this surprising turn in the weather, and to take in the flower-pots from the window sill as a precaution. To my astonishment I found the sky free of clouds and filled with stars, yet the lofty trees were tossing violently to and fro. Only when I hastened to the other side of the house did I perceive the fiery column of the burning Glass Palace directly before me. What had wakened me was the inrush of air into the conflagration, which ceased when the fire was extinguished.

tion over the urban area of Pasing and Munich. This cloudburst is, of course, not caused by the city. But it is no accident that the culmination of the process occurred right here. The location of the two

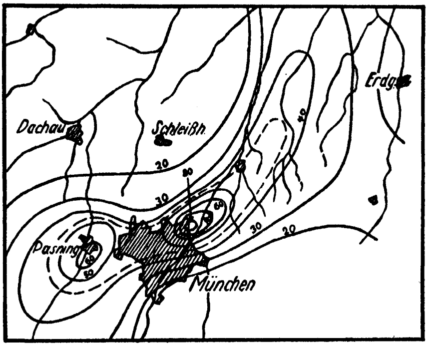

FIG. 173. The cloud burst type of rain is released over large urban area. (After J. Haeuser (from Kratzer: Das Stadtklima))

precipitation maxima in Pasing and Munich, as well as several similar instances, make it very probable that there exists here a microclimatic effect of the city, which expresses itself in the formation of weather of macroclimatic magnitude.

CHAPTER 39

The Conscious Modification of the Microclimate by Man

As man discovers his relation to microclimatic phenomena, he first gives conscious consideration to them. There follows later a willful attempt to influence and modify the microclimate.

W. Hellpach (*737*), in his work "Geopsyche," speaks of the rational climatic search which men today can and should carry on. So far as he has the opportunity he should find the climate best suited to the preservation and development of his bodily and spiritual powers. In time of sickness, when such questions are of prime importance, every good physician has always advised his patient in the choice of a suitable health resort. In such advice, as K. Büttner (*720*) has only very recently observed, microclimatic questions must receive suitable consideration. It is desirable in a climatic health resort or air "cure" that, in addition to certain healing waters or other curative means, it should possess a climate favorable to recovery. Whether this requirement is fulfilled or not in a given case, depends, in places situated in the middle or high mountains, or surrounded by forests, largely on microclimatic conditions, such as have been treated in parts V and VI of this book. Attempts have recently been made to standardize the concept of health resort in the public interest, according to verifiable climatic conditions, so as to restrain sordid advertising. K. Knoch (*740, 741*), F. Linke (*750*), A. Gregor (*732, 733*) and W. Mörikofer (*757*) have expressed themselves on this, and have submitted recommendations.

But even a healthy person can and should choose his climate intelligently, and this becomes a search for the best every-day microclimate, since the abode of man is always connected with a definite microclimate. Whoever gives some attention to this in his spare moments, even for very short intervals of time, will be astonished at the great number of previously unrealized possibilities.

These considerations apply in even greater degree to the choice of a climate for communities. E. Flach (*725*) has given suggestions for selecting summer camp locations for the Hitler youth, which are filled with microclimatic facts. In these camps the youth who in their city houses are deprived of proper light, air, sun, wind and rain, are toughened without suffering any harm to their health. The tents are set up in the air layer near the ground. The relations

of the ground and of the surroundings are consequently of great effect on the demands which day and night are placed on the young people. In the first place, a dry foundation is sought for the camp; sand is preferred. The air should be free from dust. Hence the location should not be close to settlements or main roads but near to patches of woods which filter out the dust. Places with periodically blowing winds and collecting basins of nocturnal cold air are to be avoided. The slope of the land and the surroundings should permit the free access of sunshine, without being too exposed to precipitation. If these requirements are to be fulfilled, careful attention must be paid to the microclimate of the locations.

In close connection with the conscious search for a suitable microclimate is the conscious modification of the microclimate.

It has been shown in Chapter 37 what strong repercussions the occupation of the earth by man has on the microclimate. In particular, all that has hitherto been said as to the influence of soil types, of condition of the ground and of plant cover, can serve as proof of how dependent the microclimate is on man. While the weather, and especially the macroclimate, is free from regulation by man, the microclimate is relatively easily affected and molded to his will. In this lies the far-reaching practical significance which microclimatology has for human life. Man can consciously control climatic conditions for himself and also for the plants and animals on whose welfare his own depends. The regulation partakes of the character of an adjustment of macroclimatic conditions within the range of the microclimate, where, in the final analysis, the whole life of plants, animals and man is spent.

How far man can influence the microclimate directly to his personal advantage, we can learn from the book, "Artificial Climate in Human Environment," by E. Brezina and Wilhelm Schmidt (*718*), which appeared in 1937. The microclimatic picture begins with clothing, which alters the natural heat capacity of man. The amount of material as well as its permeability to heat and to wind is so chosen that the most favorable microclimate possible is produced between skin and clothing. In "Physical Bio-climatology," by K. Büttner (*719*) we have a new book about the natural heat economy of man and how it is modified by clothing.

L. Weickmann (*765*) has constructed a thermohygrograph the size of a watch, which can be worn directly on the skin. This permits making a record of temperature and humidity in the microclimate over the skin and furnishes the data necessary to its proper regulation.

Fig. 174 represents an experimental record made on Feb. 21, 1938 by a gunner in an anti-aircraft regiment during gunnery practice. To avoid interference between the two recording pens, they have been displaced 90°. The time scale farthest from the center corresponds to the dotted humidity record, which we shall examine first. It

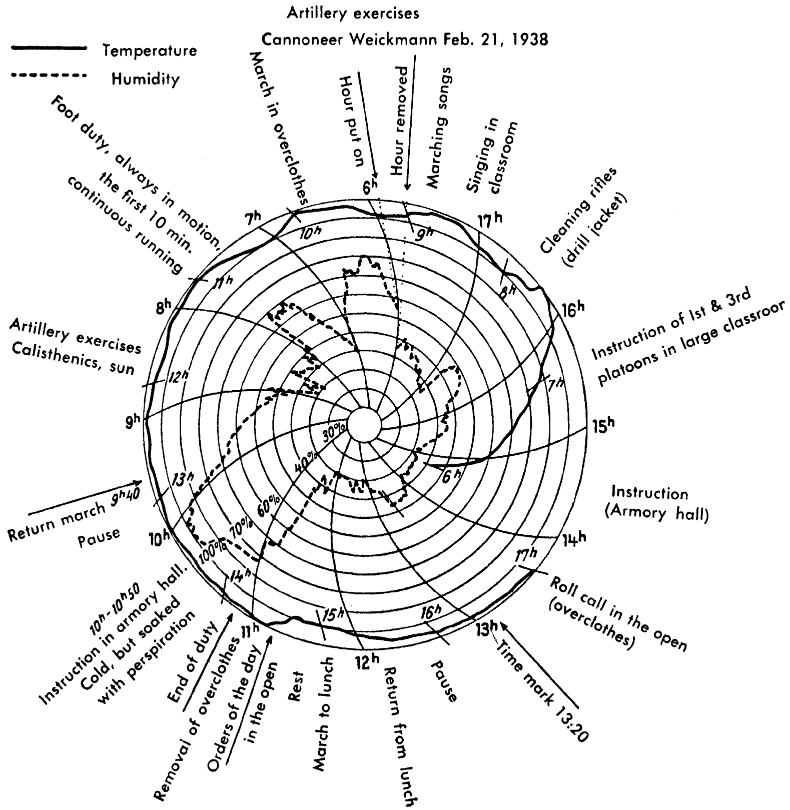

Fig. 174. Temperature and humidity recordings of the microclimate over the skin with L. Weickmann's pocket thermohygrograph

begins at the top of Fig. 174. After breakfast, the observer went outdoors at about 7 o'clock. There was a light frost, so the humidity above his skin dropped to 40%. A short but steady run causes it to rise again at once. The succeeding gunnery practice in the sun permits the humidity to fall again at first. Increased exertions, however,

bring about a steady rise, culminating in an outbreak of perspiration at about 10 o'clock, after which the humidity holds for some time at 100%. Only with removal of the outer clothing at about 11 A.M. is the desired drying off accomplished.

The temperature, the time scale for which is indicated by the fine inner figures, varies between 33° and 34° after the first rise. It is lowest, following the outbreak of perspiration between 10 and 11 o'clock. This is the sensation of "feeling chilly" one experiences when standing for a time in perspiration soaked clothes.

The next step in regulation of the microclimate we may call the "bed-climate." According to recent measurements by H. Landsberg (*745*), the temperature under the bed covering is decidedly dependent on the room temperature and, indirectly, on the outdoor temperature. The average maximum attained in the course of the night is 30°, but in a cold room it may be as low as 25°. The microclimate in bed is therefore not always a true protective climate as has been previously assumed. Adjustment to the latter condition is, however, readily accomplished by a healthy organism.

The room climate or climate of the living space has been thoroughly studied by K. Egloff (*722*) at Davos, and also by A. Amelung and H. Landsberg (*713a*) and by F. Linke (*751*). Physicians have also concerned themselves in this investigation. A compilation may be found in the book by E. Brezina and Wilhelm Schmidt (*718*).

The regulation of this microclimate, which is of such great significance for the life and activities of man, takes place in various steps.

In the first place the location of the room in the building, as to compass direction, height above ground, and surroundings, determines its microclimate so that construction represents one of the first stages in climatic control. The necessity of utilizing whole buildings and the question of cost set certain limits to this. The skill of the architect must get the best out of the location he has, using the building material at hand, and utilizing the number, form and arrangement of windows to the best advantage.

Within the limitations set by construction, further regulation proceeds by means of window ventilation or special ventilating equipment. In this way, the disadvantage is modified that in a closed room "dead inside air" exists in opposition to the "fresh outside air" (C. Dorno, *721a*). Less of the air is confined in the motionless "ground layer" near the floor. In midsummer the maximum temperatures are lowered by screening out radiation. In winter time, the

heating of the rooms improves the temperature conditions but normally is combined with a significant drying of the air.

A third step, finally, is the production of an artificial climate which is entirely independent of the surrounding weather processes. This manufactured climate is today merely a question of cost, since there are no fundamental technical obstacles to maintaining even the largest rooms at constant temperature and humidity with the admission of purified air exclusively.

This artificial climate in a limited space is unquestionably a necessity where the natural climatic conditions make human life and work impossible — for example, in the 1800 meter deep gold mine in South Africa, where the temperature of the surrounding rock is at 50°C with the air at complete saturation. It should be considered in shipping, for in certain parts of a ship, particularly the boiler-room and engine-room, a voyage in the tropics makes extraordinary demands on the personnel. These have been considered recently. Anyone who is interested in this aspect should look into the books on marine sanitation by H. Ruge (*760*) and, on the meteorological side, by T. Berké and G. Castens (*716*) H. D. Harries (*735*), H. Michler (*756*) and F. Wagner (*764*).

Furthermore, the artificial regulation of climate is desirable for houses in hot countries. In our macroclimate, the technical industries come to mind, such as tobacco processing, where the manufacture is considerably influenced by temperature and humidity conditions.

Our acclimation to the indoor-climate causes an entirely wrong idea of the macroclimate in which we are living. This is valid not only for winter time, though in this season we become aware of the cold despite the protecting clothing when we go outdoors; but also in spring and fall and even in summer we generally estimate the climate as too warm, since we escape the nocturnal portion of the daily temperature course by flight into the bed-climate. In the first World War, I made this striking discovery during the war of movement which compelled us to camp in the fields during the night.

Besides the dwelling place also the storerooms have to be taken into consideration where often goods sensitive to weather, as potatoes, milk, preserves, seed goods, flower bulbs, etc. are stored. We should not forget the air raid shelters which protect the people in the hour of peril and should not be too damp and cold. Under certain conditions, whole houses can serve to store goods and must be planned microclimatically for these goods, as is the case with refrig-

erated buildings, graneries, warehouses, places for storing overseas goods, etc. For marine shipping a special storing-meteorology exists.

Starting from the climate of the rooms we proceed *to the climate of the house.* On the basis of his personal experiences in many climates in many parts of the earth from Greenland to the South Sea, Kurt Wegener (*764b*) has given a sketch, worth reading, of how men in building their houses avoid or at least moderate the inconvenient features of the general climates except in cases with which other points of view are paramount. H. Amende (*714*) in 1938 investigated light conditions in the clinics at Jena in comparison with those of the neighboring mountain estates. It appeared that the clinics have a very unfavorable microclimatic situation, so that there is no possibility of therapy with natural light. Today, before building a clinic in a hilly country, the microclimatic conditions would be investigated with a sunshine recorder (*493*). Wilhelm Schmidt and W. Schwabl (*496*) have used this instrument in testing the suitability of different neighboring pastures for cattle. V. Conrad and W. Hausmann (*721*) attempted to find the physiography most favorable, in regard to wind conditions for a sanitarium, and recommended a gentle slope of a "carpback" shape. Such a location is free from the drafty air of passes and deep valley, it does not have the strong winds of peaks and domes, and by the shape mentioned above it avoids lee eddies, which might bring up dust from the lower ground. Furthermore, protection against wind and dust can be gained by the establishment or maintenance of forest windbreak belts. F. W. P. Götz (*731*) has praised a mountain cirque as favorable in respect to light conditions.

It is probably undisputed today that in the establishment of hospitals, sanitaria, convalescent homes, etc., microclimatic viewpoints are recognized and thoroughly considered. To teach what these considerations should be is one of the chief aims of this whole book. Suggestions on this subject are to be found in Chapter 25. The consideration should not be postponed too long. W. Hausmann (*736*) once expressed this in the following words: "It is essential to seek the advice of a climatologically inclined physician and a medically interested climatologist in regard to all buildings of a public nature, especially hospitals, convalescent homes, sports plazas, bathing resorts, etc., and such advice should have weight in city planning wherever possible. But, if this advice is to be of use, it must be had before contracts are let, for the best "medical-climatic" ideas will be wasted if the foundations have been laid according to preestablished plans.

To the initial concept of "building climate" we must append therefore, those of settlements, blocks of houses and cities. This brings us into the realm of hygiene, and here we must refer to A. Kratzer (*781*), as well as E. Brezina and W. Schmidt (*718*) in whose books further material is to be found.

In addition to the intentional modification of the microclimate in the direct interest of man, there is a similar modification for animals. Man seeks to ameliorate the living conditions of the useful domestic animals, insofar as they depend on the microclimate, and to make those of harmful animals as difficult as possible.

P. Lehmann (*747*) was probably the first to call attention to the significance of the climate in a stable and to the necessity for its systematic observation and regulation. Recently, A. Mehner and A. Linz (*755*) have published a series of temperature measurements. According to them, temperature fluctuations in an empty stable are half as great as those of the outdoors, while in an occupied stable they are only one eighth as great. On the floor they are greater than near the roof. The correlation coefficient between stable temperature and outside temperature will serve as a measure of excellence of the stable. P. A. Buxton (*501a*) gives the daily course of the temperature in a cow-stable in Palestine. Veterinarians and builders can work together in finding and producing the most favorable microclimate.

Man will deprive harmful animals of all microclimatic conditions favorable to their growth and reproduction. Several examples of this are to be found in Chapter 36. Microclimatology can also aid in the war of extermination, for only he who understands all phases in the life history of an animal can succeed in mastering it even under unfavorable circumstances.

What applies to animals in the service of man, holds true also for the plants which furnish his nourishment. At the best he furnishes the plants their own house with an artificial climate. This of course is possible only for special experimental and breeding purposes. A. Mäde and W. Rudorf (*753*) have very recently described the microclimate in a modern air-conditioned greenhouse at the Kaiser Wilhelm Institute for breeding research in Müncheberg. But even the garden breeding establishments which are not air-conditioned, such as the ordinary greenhouses and hot-beds, serve to modify the microclimate, artificially, in favor of the plants. During 1940, A. Mäde (*752*) published several series of measurements of the temperature march in such establishments, which are of basic interest in regard to observational technique.

In Section VI of this book (on the influence of plants on the microclimate) the reader has long since inferred what effect human activities in the culture of plants in the open exert on their microclimatic living conditions. Herein is the field of activity in which man is able to mold the microclimate most effectvely and adapt it to his uses. Here is the most important aim of modern microclimatology. P. Lehmann (*746*) has given a fine presentation of the possibilities which present themselves from the standpoint of purely practical agriculture.

Reference has been made repeatedly here to such practical applications. For the sake of completeness, however, two problems must be raised in particular, to which we have been unable to give sufficient attention thus far. These are the questions of artificial wind protection and artificial frost protection.

The great damage to agriculture and forestry which accompany excessive wind speeds near the ground, especially in combination with soil dryness, has been mentioned already in Chapter 37. The danger is obviated by the use of strips of shrubbery, copses and forests, which are most effective when they run at right angles to the direction of the prevailing wind. Experience in such windbreak strips has been gained on the Russian black-earth steppe between the Dnieper and the Volga, on the prairies of the United States, along the North Sea coasts of Germany and Denmark, and in several other localities.

The effect of a wind break hedge extends not only down wind but to a smaller degree also against the wind. The wind velocities, measured to establish the protecting effect, are given in per cent of the undisturbed open land speed, which is observed far outside the protected region. The range of the protecting effect is not indicated simply in meters but generally the height of the protecting hedge is used as the unit; a hedge two times as high offers protection for double the distance. But there is no agreement about the height at which the wind should be measured and with what reduction of the open land speed the protecting effect is still considered as sufficient. The wind speed, diminished in the protected zone, changes continuously to that over the open land. The statements, therefore, fluctuate within widest limits. To give an idea of the order of magnitude it may be said on the basis of the measurements of M. Woelfle (*767–769*) in Germany, and W. Nägeli in Switzerland (*757a*) that to the front the protecting effect extends against the wind to from 5 to 8 times the height of the protecting hedge, behind it to 25 to 35 times

its height. The extensive measurements of the Danish Heath Society and C. E. Flensborg (726) resulted in:

At the distance of (m) ..	5	10	20	40	60
Wind speed (%)	30–40	45–55	60–70	70–80	80–90

It goes without saying that the width and the arrangement of the protecting hedges are of importance. A hedge which can be a little blown through by wind seems to be even more advantageous than a solid wall; this can be justified by aerodynamic considerations. Further, a level area is always assumed. Naturally, in a territory slanting away from the wind, the effect reaches farther.

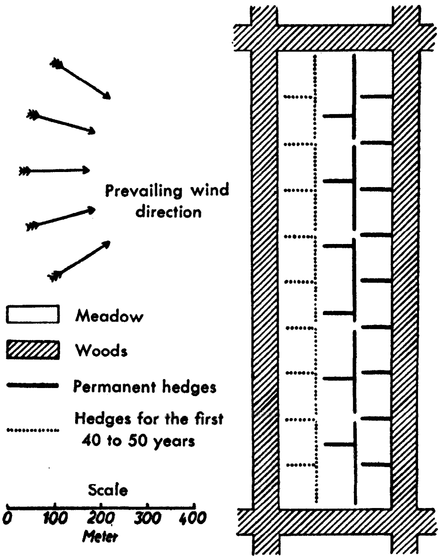

FIG. 175. Wind sheltered area of wood and hedge strips as postulated by M. Woelfle

Windbreaks according to the design of Dr. Hellmuth have been installed on the Rhone heights for the agricultural development of the plateau region. They are said to create at altitudes of from 700 to 900 m above sea level a calm microclimate for future settlements. A special study in the summer of 1937 was initated by M. Woelfle (769) to recommend the type of windbreak shown in Fig. 175.

The 50-meter shaded windbreak strips enclose the sheltered plots measuring 250 by 1000 meters. The windbreak, which consists of half of evergreens (spruce) and half of deciduous trees and which

when fully grown will be 15 m high is relatively broad, because on its windward side allowance has to be made for the adverse action of the wind, snow and frost. If at least 30 to 40% of the free wind is to be screened from the whole inner field, rows of hedges must be constructed one to two meters wide and 4 to 5 meters high. These hedges are of additional use as cow-fences for the pastures, as nesting sites for birds and as suitable repositories for the stones collected from the arable land, as well as a place to get hazelnuts. The hedgerows most sheltered from the wind, which are indicated by the dotted lines in Fig. 175, can be removed later, when the forest strips have grown high enough. The scheme of Fig. 175 will in individual cases be adapted to the particular lay of the land, soil conditions and traffic requirements. It furnishes, however, a fine example of a planned microclimate such as is possible with modern large scale planning.

The problem of artificial windbreaks belongs in general to forestry, rather than to meteorology. The difficulty consists in the use of suitable kinds of trees in the proper mixture, in the correct style and manner of planting and in the care of the windbreaks.

Of a particularly meteorological nature, however, are the questions posed by the problem of artificial frost protection. We shall speak of it as a second special practical application of microclimatology. Before we take up the discussion of the specific protective measures, some comments must be made on the origin of destructive frosts.

CHAPTER 40

Destructive Frost as a Microclimatic Phenomenon

When, in the spring, the plant world has awakened from its winter rest, night frosts continue at intervals for some time. We call them "late frosts." In a similar manner "early frosts" come before the end of the growing season. In our German macroclimate, nights with temperatures below freezing occur in certain places even in July and August. These are described as "summer night-frosts." We shall group late frosts, early frosts and summer night-frosts under the heading "destructive frosts."

The destructive frost is typically a phenomenon of the microclimate. There probably are spring nights on which, over the whole country, the blossoms freeze and the young plant growth is killed. But the general rule is, that on cold nights, cold places are visited particularly. The farmer knows in his experience, and the forester in his, of just such endangered places.

E. Münch and F. Liske (799) in 1926, in a study of frost danger to the spruces of Saxony, proved from the macroclimatic observations of the meteorological stations, the influence of physiography on susceptibility to late frosts. They separated the many years of observational data according to cold and warm locations and thus obtained the correlation shown in Fig. 176 between the number of May and June frosts and the altitude above sea level. In both instances the frequency of late frosts increases in accelerated ratio with increase of altitude. Although the nature of the macroclimatic observations made in shelters suppresses the differences found there, they are clear enough in Fig. 176. In the air space close to the ground in a given climate the number of frost nights listed on the abscissa are to be multiplied many fold.

R. Geiger, M. Woefle and L. Ph. Seip (455) have published comprehensive microclimatic observations on this question from the Bavarian forest. In Fig. 116 (ch. 24) the scattering of minimum night temperatures in the ground air on the slopes of the Great Arber was shown. The law of temperature decrease with height was recognizable only by statistical summation of the several observations and even then only above the great temperature inversions in the valleys. The influence of the microclimatic conditions was on

the contrary so decisive that a station at 800 m above sea level might be even colder on the average, and another at the same altitude warmer, than a station at 1400 m. It is obvious that this has a great influence on the relative frequency of late frosts. The predominance of the microclimatic influence over a recognized macroclimatic law, as here demonstrated, is the best possible proof that the destruction of plants by frost is a microclimatic affair.

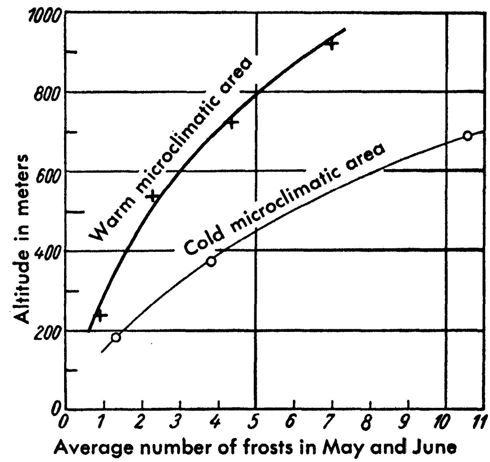

FIG. 176. Increase of frost danger with altitude in the Erz mountains. (After E. Münch and F. Liske)

Essential to the occurrence of a killing frost is the cold wave which first upsets the general temperature level. It is caused by the transport of cold air from source regions near the pole (in the case of advective frost). In addition to this there are the orographic conditions which intensify the nocturnal cold to the freezing point (radiation frost). The microclimatic laws which are in effect here are none other than those we have already enunciated throughout this whole book. It is only necessary to recapitulate them briefly with a view to practical frost protection and to refer to earlier explanations.

Local damaging frost is intensified by the following conditions:

1. by a clear sky, since this favors heat radiation outward (see Ch. 2 and Ch. 8).

2. by dry air, since water vapor increases the counter radiation of the atmosphere at night (see Ch. 2).

3. by absence of wind, since this leaves the temperature stratification by outgoing radiation undisturbed, with the coldest air next to the ground (see Ch. 11).

4. by the poor heat conductivity of the earth, which, in the first place, lessens the nocturnal movement of heat out of the ground — a movement which would reduce the temperature drop of the outward-radiating surface. In the second place, the heat supply of the ground is, on the whole, slight, for even during the day, little heat is stored up. In the third place, the high daytime temperatures associated with the poor heat conductivity excite the plants to premature spring growth on these very frost-threatened soils. (See Ch. 14.) In this class of soils belong the moors which, in spite of their high water content, are, by virtue of their structure, theoretically poor heat conductors (see Chs. 13 and 14).

5. by strong evaporation, which occurs after rainfall and in the presence of a plant cover that gives off much water because of the amount and nature of its surface area (cooling by evaporation).

6. by the local advection of cold air, especially by cold air floods, as described in detail in Chapter 18.

7. by the lack of natural protection from outward radiation, such as is afforded by every shrub and tree. This follows of course from what has been said about radiation screens at the edge of plantings. (See Ch. 35.)

It is a matter of common experience that the air over meadows or weedy crops is colder at night than that over bare soil. Differences of as much as 9°C have been measured. This can be directly observed at times by reason of the formation of hoar frost. Moreover, the fog which lies over meadows and not elsewhere usually owes its occurrence to this temperature relationship. On account of the significance of this fact for grape and fruit culture and for forestry at the time of late frosts, the designation "grass frost" has been adopted.

The most erroneous explanations for this phenomenon are current. The assumption, that the meadow is a greater nocturnal radiator of heat outward, is false. Also, the manifold multiplication of surface area by means of stalks and leaves is unimportant. (See Ch. 27.) Numerous measurements show consistently that a meadow gives off less heat by radiation at night than does the solid earth. In a fundamental work on the grass-frost, F. Sauberer (*800*) mentions, for example, an evening observation at Lunz, in March, 1937, in which, by the use of an Albrecht radiation-meter (*372*) a radiation of 0.079 cal per sq cm per min. was measured over a meadow, as compared with 0.110 cal over nearby solid ground. In agreement with the law

of the dependence of radiation on temperature, therefore, the outgoing radiation of the colder meadow is also less than that of the warmer, bare ground. Why, then, is the meadow prevailingly colder?

In the first place, there is the circumstance that there are about 20 to 50 sq meters of living leaf surface to one sq meter of ground, which are effective so far as evaporation is concerned even if not for radiation. Consequently the heat loss through evaporation is considerably higher in the case of the meadow than in that of bare ground. In the second place, the plants are on a poorly conducting foundation of decayed vegetation; this is particularly true for uncared for mossy meadows and still more so for weedy forest plantings. That there is a very large range of temperature above such a poorly conducting substratum, with especially cold nights, has been stated before (Ch. 14). Finally, when the two causes mentioned have lowered the meadow temperature, the temperature contrast in respect to the adjacent air layer becomes greater. Consequently the grass, either by convection or by radiative pseudo-conduction, withdraws more heat from the air just above it than does the solid ground. In this way is the "grass frost" to be explained.

The laws stated above as governing the occurrence of a destructive frost, make it possible to plan protective measures against it. By this we mean, not the steps to be taken when first the danger is seen to threaten, which we shall treat in the following chapter, but such as in the long run will lead to a lessening of the frost hazard.

W. J. Humphreys (797) says in one place: "The best time to protect fruit from frost is when the orchard is being laid out." The nature of the plants and the microclimate must be adapted to one another. This demands knowledge of microclimatic relationships and selection of the most suitable varieties.

For low-growing plants, protection by a screen of high trees is a decidedly effective measure. In forest practice it is common to protect the young growth with a "fore-planting" to ward off late frosts. On the Upper Bavarian plateau, for example, spruce plantations are screened by a protective growth of fast-growing birches. In northern Germany old pine slashings are used for this purpose, to allow the tender Douglas firs to reach maturity. The old stand is heavily pruned in order not to deprive the lower plants of essential sunshine. Even a heavily pruned stand of trees makes a serviceable frost screen.

H. Amann (793) has carried out microclimatic temperature meas-

urements in a stand of 32 year old birches, averaging 11 meters high, in the Anzing-Ebersberg forest. The birches covered an area of 0.88 hectares. On one side of this was a bare space in the perfectly level country, which was left for comparison. On the opposite side was an old spruce forest. The young spruces under the birches had attained a height of between 0.8 and 1.5 meters and an age of 14 years. In May, 1927, H. Amann observed the following nocturnal minima at a height of 25 cm above the ground:—

TABLE 63

Measuring Point	Barren Area		Under the Birch foreforest			
	Point I	Point II	In the border of the barren area	In the Interior		Near An Old Stand
				Point I	Point II	
May 11, 12	−11.0	−10.9	−7.3	−6.2	−5.6	−5.2
May 14, 15	− 8.0	− 7.7	−4.1	−2.6	−1.9	−2.0
May 15, 16	− 3.8	− 3.5	−1.7	+0.4	+0.6	+1.0
May 25, 26	− 2.9	− 2.1	+0.2	+1.5	+2.3	+2.5
Mean on 11 May nights	− 4.1	− 3.7	−1.3	−0.2	+0.4	+0.5
Temperature difference between 25–100 cm height	− 1.4	− 1.2	−0.4	+0.1	+0.2	+0.0

The protection of the open stand of birches resulted in a temperature gain of 4° for the average of the 11 coldest May nights. In individual cases this was as much as 6°. At the edge of the birch forest next to the bare area the excess of heat was less, while next to the old stand it was greater—an indication that a partial air exchange takes place along the borders. The difference in temperature between the heights of 25 cm and 100 cm above the ground shows clearly that the effectiveness of the fore-planting consists in the cutting down of outward radiation, for above the barren area this slight difference in height results in a temperature difference of from 1.2 to 1.4°; this is normal for the outgoing type of radiation. In the birch forest the difference is practically zero, as it is also in the old stand, a proof that it is only the advection of cold air, whether from the outward-radiating crown-space of the birches, or from the colder side areas, that determines the temperatures at the ground, and not a process of outward radiation.

It is possible to obtain further effective frost protection by con-

trolling the flow of cold air. Staudacher (*804*) was in 1924 probably the first to call attention to the fact that it is not the lay of the land alone which accounts for the accumulation of masses of cold air in a hollow but also the plant cover, which permits or hinders the movement of the air. He calls the area from which cold air masses can flow in freely to a certain point, the "source region" of the frost. He has shown that the size of this source may be subject to great variations in the course of time and that the liability of the basin to damaging frost varies with the size of the source.

In Fig. 177, *AMB* represents a cross-section of such a physiographic basin. Considering the form of the land only, the source region is bordered on each side by the elevations *A* and *B*. At night all the air between *A* and *B* will flow toward *M* as it cools. But if a circle

FIG. 177. The conception of the frost source region.

of forest *W* lies half way up the slope, the downflow of the air lying above *W* is practically stopped by the braking effect of the air movement in the forest, so that the cold lake is divided into two parts as indicated in Fig. 177. Under certain conditions this may be advantageous. The sudden increase of destructive frosts in places which previously had suffered little, is, according to Staudacher, attributable in most cases to an enlargement of the source area by artificial means. O. W. Kessler and W. Kaempfert (*813*) published a diagram of an ideal landscape which could be altered, by artificial guidance of cold-air movement and by control of water conditions, from a frost-visited area to a frost-free one.

In conclusion it may be mentioned, that security against a surprise attack by a destructive frost is a matter for *preventive* measures. Some may trust to alarm thermometers. There are various types which have been tested in practice (*813*). They are placed in the garden which is to be protected. When the temperature falls below a previously determined critical point, a bell is set ringing which calls those responsible in the emergency from their warm beds.

This method, however, gives much too short notice. It is better to make use of frost forecasts at the same time. First one should consult the weather forecast and if necessary the special frost warning of the

nearest weather bureau office. This must be modified by experience, according to the favorable or unfavorable microclimatic conditions of the garden in question. Finally one will make his own frost forecast based on his own instrumental observations.[1] There are a number of rules for this, which cannot be mentioned here. Information on the subject may be found if necessary in the work of O. W. Kessler and W. Kaempfert (*813*).

[1] In the first edition I dealt with frost forecasts in chapters 22 and 23. In discussing the work of J. Schubert on pages 196–198, I erroneously interpreted the condition which J. Schubert advanced as *necessary* for the advent of a night frost, as being a *sufficient* one. This error I gladly correct here.

CHAPTER 41

THE BATTLE AGAINST DESTRUCTIVE FROST

Frost prevention belongs almost exclusively to the time of late frosts and to the month of May in particular. The possibility of combatting destructive frosts with artificial means depends on the rarity of its occurrence, for every battle against frost demands a considerable outlay of capital and energy — in preparation, in readiness and in strenuous night work. All this can be absorbed the more easily in the conduct of a business, the more rarely a late frost occurs in the given locality.

For this reason the first successful development of artificial frost protection was in the fruit-growing regions of the United States of America. The valuable orange industry of California lies in a geographical latitude comparable in Europe to that of southernmost Italy or the northern coast of Africa. The fact that, in spite of this location, the winter frosts can do so much harm there, is based on macroclimatic conditions. In the western part of the continent the ranges of the Rocky Mts, and in the eastern part, the Alleghenies, run from north to south and lead far southward the cold-air masses which in Winter stream down intermittently from the great Canadian reservoir of cold. The cold waves under certain weather conditions are able to penetrate clear to the sub-tropical fruit belt and to induce there such low temperatures that the hope of a harvest may be dashed in a single night. This is, however, such a rare occurrence that quite an expensive outlay for combatting frost can be made to pay for itself.

Here enters another consideration. There is cheap material at hand for the oil heaters which are there used, a million of which were already in service in 1914. It is a by-product of the oil refineries in this land which is richer than all others in oil. This fact, together with the rarity of frost and the great value of the crop, makes the method practicable. In the first edition of this book the descriptions in the chapter on artificial frost protection were based almost exclusively on the experience of the United States.

In the meantime the problem has been pressed forward forcefully in Germany. Our noblest German crop, the winegrape, bears such a crop in favorable situations that artificial protection of the frost-endangered lower vineyards has seemed profitable in spite of the

great expense involved. Renewed attempts have been stimulated. During the years 1926–1928, O. W. Kessler applied the newly formulated laws of microclimatology so successfully in the Oppenheim wine district that in the month of May, 1928, alone, several hundred thousand marks worth of produce was saved by artificial methods of frost protection.

This result naturally helped the further expansion of the experiment. An "Imperial Committee on frost protection in the German wine industry" undertook the organization of research — again under the direction of O. W. Kessler. The weather service center in Hamburg established a microclimatic frost-observational network in the "four counties" under K. Bender. Wilhelm Schmidt contributed his talents for finding the proper research technique for a given problem to this practical task in the wine-producing area of Gumpoldskirchen near Vienna. After the overthrow of the government the newly founded Imperial weather service took the place of all the preceding organizations. Under the leadership of K. Knoch this research was joined with his agricultural meteorological project and was furthered by the guarantee of substantial support. A special institute at Trier, in the vineyard district of the Mosel, directed by O. W. Kessler is now the center of this research.

In 1940, O. W. Kessler and W. Kaempfert (*813*), in quite a large volume on "Prevention of Frost Damage," published the results of all the research up to that time both in Germany and elsewhere. In this book can be found a description of the more recent studies at Oppenheim in 1928 and 1929, in the Ahr valley during 1930, at Saarstein in 1931, and since 1933 in the district around Trier in particular. It is to be understood that the discussion which follows is based for the most part on this work and the results derived therefrom.

In a small business, such as a single orchard, different kinds of protective measures against frost may be successful and satisfactory. But for a large establishment only one of the many possibilities has stood up under a long trial; that is, direct heating. Nevertheless we shall have a look at all the more important methods, since the experiments connected with them furnish a fine, comprehensive enrichment of our microclimatological knowledge.

There are two fundamentally different possibilities in artificial frost fighting. Either the attempt is made to retain the heat already present and in some way prevent further decline of temperature during the critical night, or heat is artificially added. First let us consider the former possibility.

In the main it is the radiation of heat outward which accounts for the nocturnal temperature fall, as we learned in Chapter 2. Protection against radiation is therefore protection against frost, and for this there are three methods. First, the endangered plants may be covered, either singly or as a whole, with cardboard screens, caps, braided mats, boards or the like. Second, an artificial smoke screen may be laid down over the area in danger. Third, the plants may be covered with water by flooding.

As to coverings, O. W. Kessler makes a distinction between screens and caps. The screens, which are usually set up in a horizontal position, come between the plants and the night sky and absorb the radiated heat themselves, so that the plants do not cool below the air temperature and even serve as protection to the surrounding ground. Screens are most effective when the sky is clear and radiation outward is strong. By and large the gain in temperature for the plants is seldom more than 1.5°C.

While in the case of screens as here defined it is assumed that there is a free exchange of air on all sides, the cap encloses a definite air space, depending on its form and size. Fig. 178 shows, according to Wilhelm Schmidt's measurements (*817*) the temperature distribution about a cone-shaped cap such as is used in the Gumpoldskirchen area. Outward radiation from the cap cools its upper surface to (in this case) $-3°C$. The ground beneath the cap has the advantage of the radiation shield and remains at from $+4°$ to $+6°$, while the uncovered ground nearby cools off to $-2°$. With the cap, the movement of heat from the soil is made available for the enclosed air, so that caps accomplish more than screens. The frost protection of the plants under the cap now depends on whether the cold-air skin of the cap surface, or the warm-air skin on the ground, controls the temperature of the inner space. In order to diminish the influence of the cold-air skin as much as possible the cap should be constructed of non-conducting material in order that the cooling of the outer surface may be carried through as little as possible to the inner side. It is furthermore desirable that the cap should have an opening near the ground, as shown in Fig. 178. The cold air inside seems to leak out through this hole, while experience shows that cold air from the outside does not force its way in through (perhaps an effect of the cold air sliding down the steep outer surface of the cap).

We must give careful attention to these rather involved temperature relations in a very small space since, otherwise, very erroneous conclusions may be drawn. The owner of a certain garden, for instance, sought to protect part of his plants by covering them with

empty conserve cans. The supposedly protected plants froze while the others did not. The metal was a good radiator and conductor of heat, while the airspace between the tin cans and the plants was too small, and there was no outlet for the cold air along the inner wall.

With suitable form and location for the caps, a temperature gain of about 2° can be counted on. In many cases this is not enough. On account of the great labor involved in repeated coverings and uncoverings, the method is not suited to large scale installations.

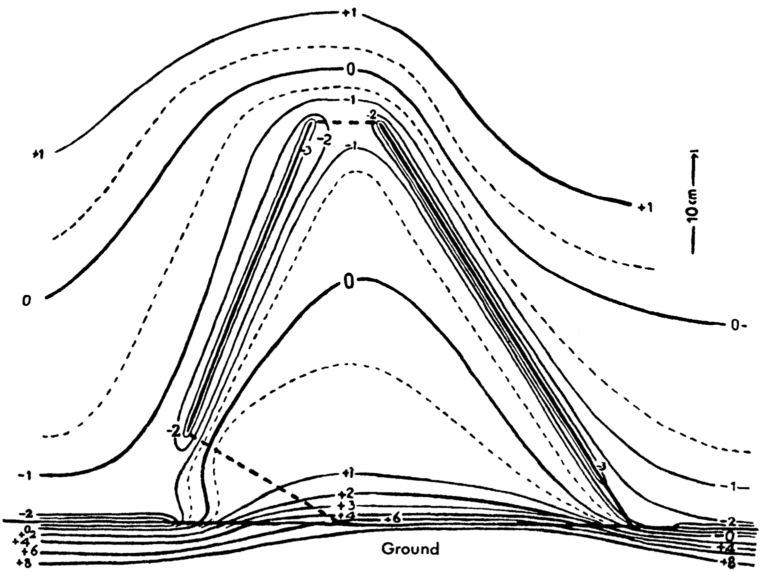

FIG. 178. Temperature distribution about a Gumpoldskirchen frost protection shelter. (After Wilh. Schmidt)

The large fixed screens which we find here and there in small business do not fall under this condemnation; they are like an oversized cap, for the air circulation under them is restricted. Properly made and applied, they furnish excellent protection but are not much used in fruit and grape culture.

Frost smoking consists in the production of smoke or fog by means of smoke cartridges or fog apparatus. The desired turbidity of the air results either from incompletely burned carbon (soot) such as the residue from the burning of large quantities of raw naphthalene,

or from chemical fog, which may be produced through the use of ammonium chloride, phosphorus pentoxide, as zinc fog, from acid fog, or in any one of many other ways. The protective action really consists in the continuous lowering of outgoing radiation in the smoke-covered district. Experiments by O. W. Kessler showed a reduction from 0.12 to 0.06 calories per sq cm per minute. For this action it is assumed that no cold air from without flows into the smoked area, and that no wind to speak of sets the artificial fog in motion during the night. This uncertainty, which is much greater in uneven country, has caused *frost-smoking* to be quite generally displaced in these days by *frost-heating.*

As the third measure for the conservation of the heat already present, we have mentioned "flooding." If the plants to be protected are entirely submerged in water, they are removed from the cold air layer near the ground and enveloped in the warm ground climate. Their frost protection is complete, since even in the most severe cold wave the most that can happen is a sheet of ice on the water surface. But only in the rare instances where the plants will tolerate such submergence and where water is quickly available in sufficient quantity, is this method practicable — in the case of cranberry culture in the U. S. A., for example.

Now let us return to the second possibility for artificial frost protection: the production of heat.

Here, too, three different paths may be followed. Apropos of the flooding we have just mentioned, let us first take up artificial watering as a frost protection.

The heat afforded by this method is the freezing heat of water. If 1 g of water at 0°C becomes ice at 0°C, 80 calories are released — the same amount of heat which is consumed by the melting process when passing from the solid to the liquid phase. When it has begun to freeze, and the endangered plants are then sprinkled (not by any means sooner!), an ice coating is at once formed about the wet leaves, twigs and stalks. The heat of freezing which is thereby released, hinders a further temperature drop as long as the water supply is sufficient (about 2 liters per sq m per hour). It is evident that the sprinkling cannot be halted but must be continued — not only till the frost is over but until the temperature rises considerably above zero, for as soon as sprinkling ceases, evaporation sets in, with a consequent cooling which must not again reduce the plant temperature below freezing.

Experience teaches that even the most sensitive vegetation, such as tomatoes, for example, will survive unharmed when the outside temperatures are several degrees below zero (in one case which came to our attention, as much as $-7°$). The plant temperature held steadily at $-0.5°C$.

From the nocturnal stratification of the ground air, we know (see Ch. 2) that warmer air is always to be found at some distance above the ground. We can therefore consider the possibility of producing a vertical mixture of the air by ventilation, thereby bringing warmth down to the neighborhood of the ground.

Artificial convection should be a means of artificial frost control. We could upset the air stratification by means of machines, as the sun does naturally when it rises. Such a process is probably possible, by using great electric fans, but insufficient for the needs of the whole country. The gain in temperature is only about 1° and would extend only about 30 meters from the fan, at most. This method, consequently, would be expensive in application, though it is used in the United States in combination with heaters.

For practical protection against frost damage—especially on a large scale—there remains only the last method, still to be discussed—the direct production of warmth by heating. At first thought it may seem ridiculous to "heat the outdoors," like a room, on cold nights. We might think the outlay in fuel could never be justified by the savings to be made. Yet all experiments in Germany and the United States show that this method is the only one which is both possible and practical.

There are three means of heating. Where oil is cheap, as it is in the United States, oil-heaters are employed. Fig. 179 shows a California fruit orchard on level ground. The heaters were built in from the first, 200 or 300 of them per hectare. At the edge of the orchard they are somewhat closer together than in the middle. At the critical time in the winter they are kept filled from an oil truck. When frost comes they are lighted as rapidly as possible. Sequence and number to be lighted depends on weather conditions (wind direction and temperature).

In Germany, hard coal, brown coal, briquettes or wood is burned in the heaters. There are a number of types of burners, easily portable, easy to service and very economical in fuel consumption. Heating is most effective when there is about one heater to every 50 sq meters, and when each heater produces at least 10,000 calories per hour. Fig. 180 shows a vineyard in a tributary valley of the Saar on the occasion of one of Kessler's experiments during the

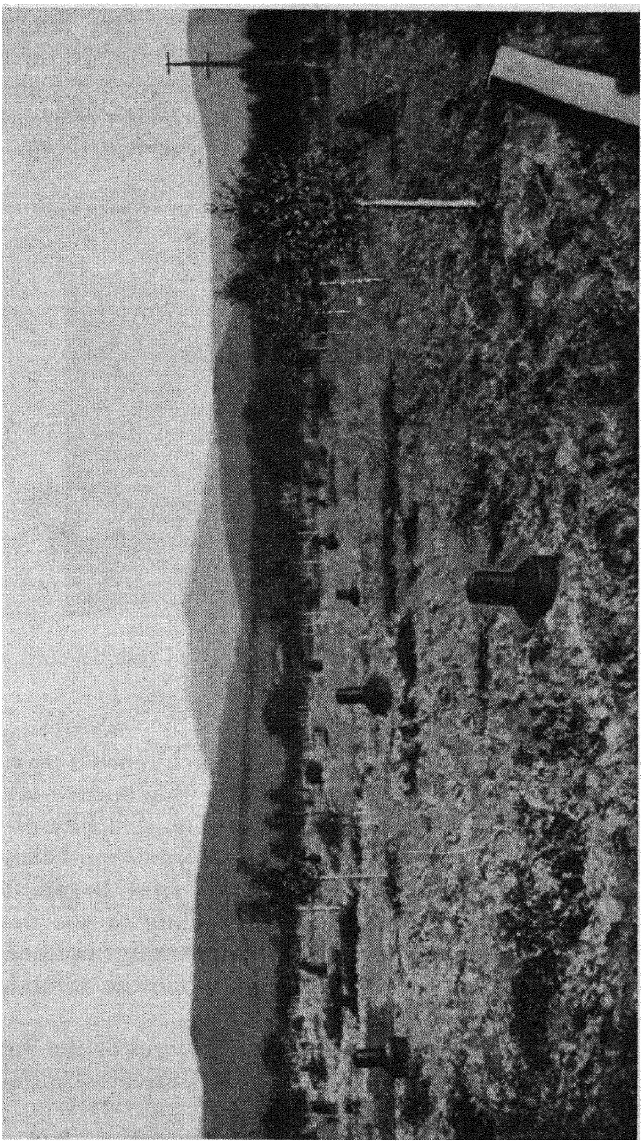

FIG. 179. **Placement of oil heating stoves in a newly planted fruit grove in U. S. A.**
(After Monthly Weather Review, 1923)

night of May 2–3, 1935. Seven rows of briquette burners had been installed and had just been lighted when this picture was taken. The first row can be clearly seen on the lower boundary wall of the vineyard. These heaters were 4½ meters apart. Five lines above stood the second row of heaters, whose smoke can just be discerned. The spacing of these heaters was somewhat greater (5½ meters). The higher up, the farther the rows were apart and the greater the spacing between heaters, for the heat produced of course moved up the slope.

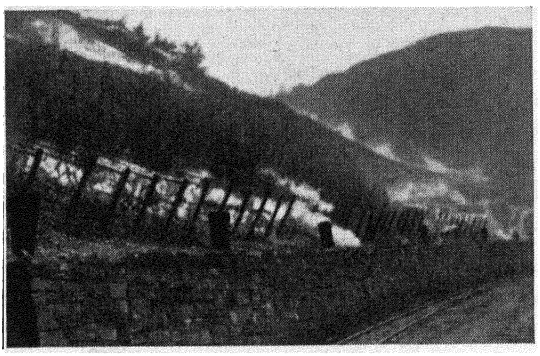

FIG. 180. Briquet heating ovens in a vineyard will be lighted with the onset of night frosts

The simplest method is the third one, in which there is no cost for equipment. Briquettes were placed out in the open — say four briquettes, at distances of 1.4 meters apart. The difficulty of quick kindling was met by introducing a mass of raw napthalene and sawdust between the briquettes. When the frost began, it was possible for two men to accomplish the kindling of 160 heaps of briquettes in 25 minutes, in spite of preceding rainy weather — the first pouring petroleum over the kindling, while the second set it aflame with a soldering torch.

Electrical heating by the use of the support wires of the vineyard has been attempted. It is, however, too expensive to install and operate.

The heating process is, more than the others, independent of topography and can be easily suited to the threatening danger. A temperature rise of from 3° to 4° is commonly attained with proper distribution of the fires. Fig. 181 shows the temperature measure-

ments 50 cm above the ground on an experimental area 63 meters square (outlined surface), on which 100 oil-heaters (Maurer pattern) were used. O. W. Kessler conducted the experiment at Oppenheim on April 26, 1929. Within the experimental plot, 17 thermometers were distributed; outside, there were 28. The initial temperatures, before heating began, lay between 6.0° and 6.5°C (Upper left-hand plan). After lighting the first heaters at 10:15 P.M. the temperature in the midst of the experimental field rose to 8°, while at the south

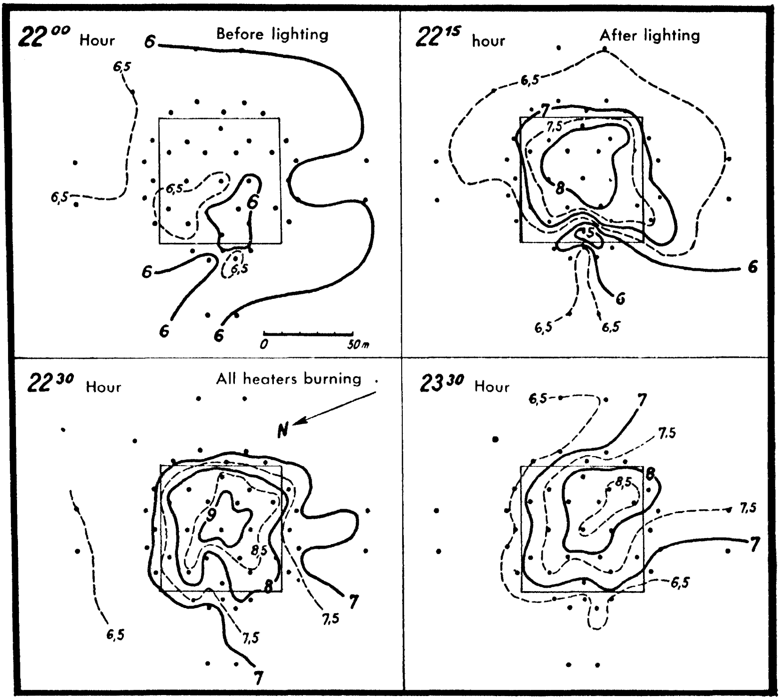

FIG. 181. Lines of equal temperature near the ground in a heating experiment with oil heaters. (After O. W. Kessler)

edge where the heaters were not yet burning there was a drop to 5°. Was this a sucking in of cold air by the first fire? A quarter of an hour later, when all the heaters were burning (lower left-hand plan), we find a good, uniform distribution of the warm zone, with the temperature 3° warmer in the middle. At this reading the temperature holds for some time, as shown by the distribution of the

isotherms an hour later (lower right). The only change is that a light wind has displaced the warm center somewhat to the side.

According to the data of O. W. Kessler and W. Kaempfert, the cost of heat production amounts to only from 1% to 2% of the damage which might be expected. It is, therefore, thoroughly practicable in vineyards and valuable orchards.

LITERATURE

Abbreviations

Ann. d. Hydr. = Annalen der Hydrographie und Maritimen Meteorologie, published by the Deutsche Seewarte. Mittler & Sohn, Berlin.
Abh. Pr. Met. I. = Abhandlungen des Preussischen Meteorologischen Instituts, Berlin.
Ark. f. Mat. = Arkiv för Matematik, Astronomi och Fysik, Stockholm.
Beih. z. Botan. Centralbl. = Beihefte zum Botanischen Centralblatt, G. Fischer, Jena.
Beitr. Phys. d. fr. Atm. = Beiträge zur Physik der freien Atmosphäre. Akademische Verlagsgesellschaft, Leipzig.
Ber. D. Bot. G. = Berichte der Deutschen Botanischen Gesellschaft. G. Fischer, Jena.
Biokl. B. = Bioklimatische Beiblätter der Meteorologischen Zeitschrift. Fried. Vieweg & Sohn, Braunschweig.
C. R. Paris = Comptes Rendus des séances de l'Académie des Sciences, Paris.
Forstw. C. = Forstwissenschaftliches Centralblatt. P. Parey, Berlin.
Geograf. Ann. = Geografiska Annaler, Stockholm.
Gerl. B. = Gerlands Beiträge zur Geophysik. Akademische Verlagsgesellschaft, Leipzig.
Jahrb. f. wiss. Bot. = Jahrbücher für wissenschaftliche Botanik. Gebr. Borntraeger, Berlin.
La Mét. = La Méteorologie, Paris.
Met. Mag. = The Meteorological Magazine, London.
Met. Z. = Meteorologische Zeitschrift. Friedr. Vieweg & Sohn, Braunschweig.
M. W. Rev. = Monthly Weather Review, United States Department of Agriculture, Washington.
Naturw. = Die Naturwissenschaften. Jul. Springer, Berlin.
Planta = Planta. Archiv für wissenschaftliche Botanik. Jul. Springer, Berlin.
Quart. J. = The Quarterly Journal of the Royal Meteorological Society, London.
R. f. W. Wiss. Abh. = Wissenschaftliche Abhandlungen, Reichsamt für Wetterdienst, Berlin.
Sitz-B. Berlin. Akad. = Sitzungsberichte der Preussischen Akademie der Wissenschaften zu Berlin.
Sitz.B. Wien. Akad. = Sitzungsberichte der Akademie der Wissenschaften in Wien. Mathematisch-naturwissenschaftl. Klasse.

Tät-B. Pr. Met. I. = Tätigkeitsbericht des Preussischen Meteorologischen Instituts, Berlin.
Thar. Forstl. Jahrb. = Tharandter Forstliches Jahrbuch. P. Parey, Berlin.
Veröff. Geoph. I. Leipzig = Zweite Serie der Veröffentlichungen des Geophysikalischen Instituts der Universität Leipzig.
Wetter = Das Wetter, Monatsschrift für Witterungskunde. O. Salle, Berlin.
Z. f. angew. Met. = Zeitschrift für angewandte Meteorologie. Akademische Verlagsgesellschaft, Leipzig.
Z. f. F. u. Jagdw. = Zeitschrift für Forst- und Jagdwesen. Jul. Springer, Berlin.

To the Introductory Chapter

(General works, bibliographies, histories of microclimatology)

1. Filzer, P., Aus. d. Frühzeit bioklimat. Forschung. * D. Biologe *5*, 168–172, 1936.
2. Geiger, R., Mikroklimatologie. * Z. f. angew. Met. *45*, 74–85, 1928.
3. —, Die vier Stufen d. Klimatalogie. * Met. Z. *46*, 7–10, 1929.
3a. —, Über selbständige u. unselbst. Mikrokl. * Met. Z. *46*, 539–544, 1929.
4. —, Mikroklima u. Pflanzenklima. * Handb. d. Klimat. I D. Berlin, Borntraeger, 1930.
5. —, D. Mikrokl. u. s. Bedeutung f. d. belebte Natur. * Z. f. angew. Met. *48*, 137–146, 1931.
5a. —, Mikroklimatologie: Rückblick und Ausschau * Met. Rundschau *1*, 140–144, 1947.
6. Geiger, R. & Schmidt, W., Einheitl. Bezeichn. in kleinklimat. u. mikroklimat. Forschung. * Biokl. B, *1*, 153–156, 1934.
7. Grimm, H., Justus v. Liebig u. d. Mikroklimatol. * Z. f. angew. Met. *48*, 30, 1931.
7a. Härtel, O., Mikroklimaforschung und Pflanzenphysiologie * Z.f.d. ges. Naturwiss. 1944, 19–27.
8. Kassner, C., Z. Geschichte d. Mikroklimat. * Met. Z. *51*, 393–394, 1934.
9. Knoch, K., Allgemeine Klimalehre. * Handb. d. Klimatol. v. J. v. Hann. 4. Aufl. I. Bd. Engelhorn, 1932.
10. —, Angew. Klimatol. als. Förderer wirtschaftl. Probleme. * Met. Z. *54*, 470–471, 1937.
10a. Knoch, K. Weltklimatologie und Heimatkunde * Met. Z. *59*, 245–249, 1942.
11. Korotkewitsch, V. N., E. Übersicht der d. Mikroklima umfass. Arbeiten. * Transact. Centr. Geophys. Obs. Leningrad *6*, 1936.
12. Kraus, Gregor, Boden u. Klima auf kleinstem Raum. Jena, Fischer, 1911.
13. Ramdas, L. A., Agricultural Met. * Current Science, *1*, 191–192, 1933.

14. —, Micro-Climatology. * Current Science, 2, 445–447, 1934.
15. Reichsamt für Wetterdienst, Bibliograph. Ber. a. d. Gebiet d. Agrarmet. Seit 1934.
16. Sanson, J., Résult. génér. d'une enquête etc. * La Mét. *6*, 69–97, 1930.
17. Scaëtta, H., Terminologie climat., bioclimat. et microclimat. * La Mét. *11*, 342–347, 1935.
18. Schmidt, Wilh. and others, Bioklimat. Unters. im Lunzer Gebiet. * Naturw. *17*, 176–179, 1929.
19. Schmidt, Wilh., Neue Wege met. Forsch. u. i. Bedeut. f. Praxis u. Leben. * Deutsche Forschung 18, 79–114, 1933.
20. —, D. Biokima als Kleinkl. u. Mikrokl. * Biokl. B. *1*, 3–6, 1934.
21. Schubert, J., D. Klima d. Bodenoberfl. u. d. unteren Luftschicht in Mitteleuropa. * Blanck, Handb. d. Bodenlehre II. Jul. Springer, 1929.
22. —, Grundl. d. allgem. u. forstl. Klimakunde. * Z. f. F. u. Jagdw. *62*, 689–705, 1930; *64*, 715–734, 1932; *72*, 257–273, 1940.
23. Tagungsberichte der Kommission f. Agrarmeteorolog. in d. Org. Met. Internat. Tagungen: Utrecht 1923, Zürich 1926, Kopenhagen 1929, München 1932, Salzburg 1937.
25. Erste landwirt.-meteorolog. Tag., veranstalt. v. d. österr. Gesellsch. f. Meteorolog. Wien 1930.
26. Conf. Empire Met. 1929, Agricult. Sect. London 1929.
27. Ann. Report Agric. Branch. India Met. Dep. Since 1933.

Bibliography for Part I

Chapter 1. Midday Heat Exchange at the Ground Surface. The Incoming Radiational Type.

28. Alt, E., D. Stand d. met. Strahlungsprobl. * Met. Z. *46*, 504–513, 1929.
29. Baur, F. & Philipps, H., D. Wärmehaush. d. Lufthülle d. Nordhalbkugel im Jan. u. Juli. * Gerls. B. *42*, 160–207, 1934.
30. Flower, W. D., Sand Devils. * Met. Office London, Profess. Notes *71*, 1936.
31. Härtel, O., D. Alpenlabor. d. Botan. Staatsanst. d. Univ. München auf d. Schachen. * Biokl. B. *4*, 65, 1937.
32. v. Holzhausen, H., Beob. e. Kleintrombe. * Met. Z. *54*, 307, 1937.
32a. Ives, R. L. Behavior of Dust Devils. * Bull. Am. Met. Soc. *28*, 168–174, 1947.
33. Lauscher, F., D. Zunahme d. Intensität d. Sonnenstr. mit d. Höhe. * Gerl. B. *50*, 202–215, 1937.
34. Marten, W., D. Strahlungsklima v. Potsdam. * Abh. Pr. Met. I. *8*, Nr. 4, 1926.
35. Mörikofer, W., Klimatolog. Einflüsse d. Hochgebirges. * Verh. d. Deutsch. Ges. f. innere Med. Wiesbaden 1935, S. 501.

36. Rossmann, F., D. Bewegungsgesetz d. Kleintromben. * R. f. W. Wiss. Abh. *3*, Nr. 4, 1937.
37. Schlichting, H., Kleintrombe. * Ann. d. Hydr. *62*, 347–348, 1934.
38. Schober, H., Beob. d. Ablösung e. Luftwirbels bei starken Temp. Untersch. in d. bodenn. Luftschicht. * Met. Z. *51*, 193–194, 1934.
39. Schubert, J., D. Sonnenstrahl. im mittl. Norddeutschl. nach d. Messungen in Potsdam. * Met. Z. *45*, 1–16, 1928.
40. Sinclair, J. G., Temp. of the soil and air in a desert. * M. W. Rev. *50*, 142, 1922.
41. Smoliakow, P. T., Zur Theorie d. Gleichgew. d. bodenn. Luftschicht. * Gerl. B. *44*, 321–336, 1935.
42. Wegener, A., Staubwirbel auf Island. * Met. Z. *31*, 199–200, 1914.
43. —, Wind- u. Wasserhosen in Europa. * Braunschweig, Friedr. Vieweg & Sohn, 1917.

Chapter 2. Nocturnal Heat Exchange at the Ground Surface. The Outgoing Radiational Type.

44. Ångström, A., Stud. of the nocturnal radiation to space. * Astrophys. J. Chicago *37*, 305–321, 1913 and *39*, 95–104, 1914.
45. —, A study of the radiation of the atmosphere. * Smithsonian Miscell. Coll. *65*, N. 3, 1915.
46. —, Ü. d. Gegenstrahlung d. Atmosph. * Met. Z. *33*, 529–538, 1916 and *34*, 14–24, 1917.
47. —, Record. nocturn. rad. * Medd. Stat. Met. Hydr. Anst. Stockholm *3*, Nr. 12, 1927.
48. —, Messung d. nächtl. Ausstrahlung im Ballon. * Beitr. Phys. d. fr. Atm. *14*, 8–20, 1928.
49. —, Über Variationen d. atmosph. Temp. strahlg u. ihren Zusammenhang mit d. Zusammensetz. d. Atmosph. * Gerl. B. *21*, 145–161, 1929.
50. —, Effect. rad. during the second internat. Polar Year. * Medd. Stat. Met. Hydrogr. Anst. Stockholm Nr. 8, 1936.
51. Asklöf, S., Ü. d. Zusammenhang zw. d. nächtl. Wärmeausstrahl., der Bewölk. u. d. Wolkenart. * Geograf. Ann. *2*, 253–259, 1920.
52. Brocks, K., Nächtl. Temp. minima in Furchen m. verschied. Böschungswinkel. * Met. Z. *56*, 378–383, 1939.
53. Defant, A., Ausstrahlung, nächtl. Abkühlung u. Bewölkung. * Geograf. Ann. *4*, 99–108, 1922.
54. Dubois, P., Nächtl. effekt. Ausstrahlung. * Gerl. B. 22, 41–99, 1929.
55. Eckel, O., Mess. d. Ausstrahl. u. Gegenstrahl. auf d. Kanzelhöhe. * Met. Z. *51*, 234–235, 1934.
56. Ertel, H., Methoden u. Probl. d. dynamischen Met. Berlin, J. Springer, 1938.

57. Falckenberg, G., Muldenfrost u. Frostflächen in Waldlichtungen. * Met. Z. *48*, 22–25, 1931.
58. Hasché, E., Z. Mess. d. langwell. Himmels- u. Erdstrahlung. * Gerl. B. *42*, 228–231, 1934.
59. Hellmann, G., Ü. d. nächtl. Abkühlung d. bodenn. Luftschicht. * Sitz-B. Berlin. Akad. *38*, 806–813, 1918.
60. Kimball, H. H., Nocturnal radiation. measur. * M. W. Rev. *46*, 57–70, 1918.
61. Krügler, F., Nächtl. Wärmehaush. messungen an d. Oberfläche e. grasbewachsenen Ebene. * R. f. W. Wiss. Abh. *3*, Nr. 10, 1937.
62. Lauscher, F., Bericht ü. Mess. d. nächtl. Ausstrahlung auf d. Stolzalpe. * Met. Z. *45*, 371–375, 1928.
63. —, Warmeausstr. u. Horizonteinengung, I. Teil. * Sitz-B. Wien. Akad. *143*, 503–519, 1934.
64. —, Dampfdruck u. Ausstrahl. in e. Gebirgsland. * Gerl. B. *51*, 234–249, 1937.
65. Linke, F., D. nächtl. effekt. Ausstrahl. unter verschied. Zenitdistanzen. * Met. Z. *48*, 25–31, 1931.
66. Meinander, R., Ü. d. nächtl. Wärmeausstrahl. in Helsingfors. * Soc. scient. fennica. Comment. Phys.-Mathem. *4*, Nr. 16, 1928.
67. Möller, F., Bemerk. z. Wärmebilanz d. Atmosph. u. d. Erdoberfläche. * Gerl. B. *47*, 215–217, 1936.
68. Petterssen, S., Ein typ. Beispiel v. Ausstrahl.inversionen in e. heit. Sommernacht. * Met. Z. *45*, 72–74, 1928.
68a. Philipps, H., Zur Theorie der Wärmestrahlung in Bodennähe. * Gerl. B. *56*, 229–319, 1940.
69. Raman, P. K., Heat radiation from the clear atmosph. at night. * Proc. Indian Acad. Sciences *1*, 815–821, 1935.
70. —, Studies in atmosph. radiation. * Ibid. *4*, 243–253, 1936.
71. Ramdas, L. A., Sreenivasiah, B. N. u. Raman, P. K., Variation in the nocturnal rad. from the sky with zenith dist. a. with time during the night. * Ibid. *5*, 45–55, 1937.
71a. Seemann J. & Löw. K. Die Auswirkung der Taubildung auf den Temperaturverlauf in der bodennahen Luftschicht * Met. Z. *61*, 158–161, 1944.
72. Süssenberger, E., D. nächtl. effekt. Ausstrahl. unter verschied. Zenitdistanzen. * Met. Z. *52*, 129–132, 1935.
73. —, Neue Unters. ü. d. nächtl. effekt. Ausstrahl. * Gerl. B. *45*, 63–81, 1935.
73a. —, Die Bedeutung des Ozons und der Kohlensäure in der Atmosphäre für die nächtliche effektive Ausstrahlung am Erdboden * Ann. d. Hydr. *71*, 222–226 1943.
74. Trojer, H., Temp.-Strahl.Mess. mit d. Parabolspiegel. * Met. Z. *57*, 149–152, 1940.

75. Wegener, K., D. Strahlung d. Bodens. * Met. Z. 55, 133–137, 1938.
76. Wegener, K. & Trojer, H., D. Temp.strahl. d. Erde u. ihre Messung. * Ann. d. Hydr. 67, 424–432, 1939.

Chapter 3. True Heat Conduction. The Normal Course of Ground Temperature.

(See also bibliography to Chapter 13)

77. Ångström, A. & Petri, E., En ny jordtermometer och nagra observ. över jordtemp. i. Stockholmstrakten. * Tekn. Tidskr. 1928, Heft 23.
78. Büttner, K., D. Wärmeübertragung d. Leitung u. Konvektion, Verdunstung u. Strahl. in Bioklimat. u. Met. * Abh. Pr. Met. I. *10*, Nr. 5, 1934.
78a. Geiger, R., Wärmehaushaltskonstanten für den Agrarmeteorologen * Met. Rundschau *1*, Nr. 11–12, 322–329, Mai-Juni 1948.
79. Hecht, W., Bioklim. Vers. z. Erforsch. d. Ursachen d. Gehaltsschwank. d. Arzneipflanzen III. * Heil- u. Gewürzpflanzen (Freising-München) *16*, 1–57, 1934/35.
79a. —, Bioklimatische Versuche zur Erforschung der Ursachen der Gehaltsschwankungen der Arzneipflanzen * Heil- und Gewürzpflanzen 1942 Heft 2.
80. Herr, L., Bodentemp. unter besond. Berücksichtigung d. äusseren met. Faktoren. * Diss. Leipzig 1936.
81. Homén, Th., Ü. d. Bodentemp. in Mustiala. Helsingfors 1896.
82. —, D. tägl. Wärmeumsatz im Boden u. d. Wärmsestrahl. zw. Himmel u. Erde. * Leipzig 1897.
83. Keränen, J., Wärme- u. Temp.-verhältn. d. obersten Bodenschichten. * (Einführung in d. Geophysik II.) Berlin, J. Springer, 1929.
84. Kühl, W., D. jährl. Gang d. Bodentemp. in verschied. Klimaten. * Gerl. B. *8*, 499–564, 1907.
85. Leyst, E., Ü. d. Bodentemp. in Pawlowsk. * Rep. f. Meteorol. *13*, Nr. 7, 1890.
86. —, Unters. ü. d. Bodentemp. in Königsberg. * Schr. d. phys.-ökonom. Ges. Königsberg 33, 1–67, 1892.
87. Maurer, J., Bodentemp. u. Sonnenstr. in d. Schweiz. Alpen. * Met. Z. *33*, 193–199, 1916.
88. Meinardus, W., Bodentemp. in d. Wüste bei Schellal, Oberägypten. * Götting. Nachr., mathem.-physik. Kl., neue Folge, *1*, Nr. 1, 1935.
89. Rambaut, Undergr. temp. at Oxford as determined by . . . therm. * Radcliffe Obs. Met. Obs., Oxford, *51*, 101–204, 1911–15.
89a. Ravet, J., La temp. du sol à Tahiti. * Ann. Phys. Globe France d'outre-mer *6*, 134–135, 1939.
90. Schmidt, A., Theoret. Verwert. d. Königsberger Bodentemp. beob. * Schr. d. phys.-ökonom. Ges. Königsberg *32*, 97–168, 1891.

91. Schubert, J. D. jährl. Gang d. Luft- u. Bodentemp. u. d. Wärmeaustausch im Erdboden. Berlin, J. Springer, 1900.
92. —, D. Verhalten d. Bodens gegen Wärme. * Hdb. d. Bodenlehre, her. v. E. Blanck, *6*, 342–375, 1930.
93. Siegenthaler, J., Bodentemp. in Abhäng. v. äuss. met. Faktoren. * Gerl. B. *40*, 305–332, 1933.
94. Süring, R., D. tägl. Temp.gang in gering. Bodentiefen. * Abh. Pr. Met. I. *5*, Nr. 6, 1919.
95. Wild, H., Ü. d. Bodentemp. in St. Petersburg u. Nukuss. * Rep. f. Meteorol. *6*, Nr. 4, 1878.
96. Woeikof, A., Probleme d. Bodentemp. Typen ihrer vertikalen Verbeit. Verhältn. z. Lufttemp. * Met. Z. *21*, 50–62, 399–408, 1904.
96a. Yakuwa, R., Über die Bodentemperatur von Kobe. * Mem. Imp. Marine Obs. Kobe *3*, 81–90, 1928.

Chapter 4. Eddy Diffusion and its Significance.

(Complete bibliography on the question of mass exchange up to year 1939 in the book by H. Lettau (*108*). Here only the later publications or those not included by Lettau are listed, and those to which specific reference is made in the text.)

96b. Albrecht, F. Turbulenzuntersuchungen * Met. Z. *60*, 109–121, 1943.
97. Ångström, A., D. Konvektion der Luft. * Met. Z. *36*, 348, 1919.
98. Berg, H., Mess. d. Austauschgrösse d. bodenn. Luftschichten. * Beitr. Phys. d. fr. Atm. *23*, 143–164, 1936.
99. Best, A. C., Horizontal temp. diff. over small distances. * Quart. J. *57*, 169–175, 1931.
100. Büdel, A., E. photogramm. Methode z. Stud. d. Ström.- u. Austauschvorgänge. * Beitr. Phys. d. fr. Atm. *20*, 9–17, 1933.
101. —, Individuelle Beweg. kleiner Luftmassen. * Ibid *20*, 214–219, 1933.
102. Geiger, R., Temp.struktur u. Mikroklima. * Met. Z. *47*, 425–430, 1930.
103. —, Met. Beob. b. d. Mittelfränk. Kieferneulenbekämpfung m. Flugzeug u. Motor i. Frühjahr 1931. * Z. f. angew. Entomol. *19*, 207–222, 1932.
104. Gödecke, K., Mess. d. atmosph. Turbulenz in Bodennähe m. e. Hitzdrahtmethode. * Ann. d. Hydr. *63*, 400–410, 1935.
105. Grunow, J., Vers. m. pendelnden Druckplatten. * Tät-B. Pr. Met. I. 1933, S. 92–95.
106. Hornberger, Studien ü. Luft- u. Bodentemp. * Forstw. C. *24*, 479–498, 1902.
106a. Koch, H.-G., Über Temperatur u. Austausch innerhalb der Bodeninversion * Gerl. Beitr. *49*, 407–426, 1937.

107. Lettau, H., Turbul. Schwank. v. Wind u. Temp. in d. bodenn. Luftsch. als Austauschproblem. * Ann. d. Hydr. *62*, 469–473, 1934.
108. Lettau, H., Atmosphärische Turbulenz. * Akad. Verl. Ges. Leipzig, 1939.
108a. Raethjen, P., Zum Wärmestrom der Turbulenz. * Ann. d. Hydr. *72*, 129–132, 1944.
109. Rempe, H., Unters. ü. d. Verbreitung d. Blütenstaubes durch d. Luftströmungen. * Planta *27*, 93–147, 1937.
109a. Rombakis, S., Über die Verbreitung von Pflanzensamen und Sporen durch turbulente Luftströmungen. * Z. f. Met. *1*, 359–363, 1947.
110. Rossmann, F., Strömung in d. Streichholzschachtel. * Met. Z. *52*, 77, 1935.
111. Schmauss, A., Schichtenbild. in Flüssigkeiten. * Met. Z. *49*, 203–204,, 1932.
112. Schmidt, Wilh., Die Struktur d. Windes. * Sitz-B. Wien. Akad. *138*, 85–116, 1929.
113. —, D. Massenaustausch in freier Luft u. verwandte Erscheinungen. Probl. d. kosm. Physik 7. Hamburg, H. Grand, 1925.
114. Wegener, A., Ü. turbul. Beweg. in d. Atmosph. * Met. Z. *29*, 49–59, 1912.

Chapter 5. Long Wave Radiation.

115. Albrecht, F., D. Wärmeumsatz durch d. Wärmestrahl. d. Wasserdampfs in d. Atmosph. * Z. f. Geophysik *6*, 421–435, 1930.
115a. Brunner, B. H.-Ch., Küsteneinfluss auf Temperatur u. Feuchte der bodennahen Luftschichten. * Gerl. B. *56*, 113–154, 1940.
116. Falckenberg, G., Neue Unters. ü. d. Bildung v. Bodeninversionen. * Met. Z. *44*, 108–109, 1927.
116a. —, Äerol. Stud.reise d. Drachenboots d. Rostocker Luftwarte. * Met. Z. *45*, 55–60, 1928.
117. —, Experimentelles zur Absorpt. u. Emm. d. atmosph. Eigenstrahl. dünner Luftsch. * Met. Z. *48*, 135–139, 1931.
118. —, D. Einfluss d. Wellenlängentransformation auf d. Klima bodenn. Luftsch. u. d. Temp. d. fr. Atm. * Met. Z. *48*, 341–346, 1931.
119. —, Exp. z. Absorpt. dünner Luftsch. f. infrarote Strahlung. * Met. Z. *53*, 172–175, 1936.
120. —, Exp. z. Druckabhängigk. d. Absorpt. d. Wasserdampfes u. d. Kohlensäure f. d. infrarote Schwarzstrahl. * Met. Z. *55*, 174–177, 1938.
121. —, Exp. z. Eigenstrahl. dünner wasserdampfhalt. Luftsch. * Met. Z. *56*, 72–75, 1939.
122. —, Exp. z. Temp.abhängigk. d. infraroten Absorpt. wasserdampfhalt. Luft. * Met. Z. *56*, 415–417, 1939.

122a. —, Exp. z. Temperaturabhängigkeit der infraroten Absorption wasserdampfhaltiger Luft. * Met. Z. *56*, 415–417, 1939.
123. Falckenberg, G. & Stoecker, E., Bodeninversion u. atmosph. Energieleitung durch Strahl. * Beitr. Phys. d. fr. Atm. *13*, 246–269, 1927.
124. Fowle, F. E., Water-vapor transparency to low-temp. radiation. * Smithsonian Miscell. Coll. *68*, Na. 8, 1917.
125. Hettner, Ü. d. ultrarote Absorpt.-spektrum d. Wasserdampfs. * Diss. Berlin 1918.
125a. Möller, F. Grundlagen eines Diagramms zur Berechnung langwelliger Strahlungsströme. * Met. Z. *61*, 37–45, 1944.
126. Mügge, R., Wärmestrahl. zw. Himmel u. Erde. * Met. Z. *46*, 514–520, 1929.
127. Schnaidt, F., Z. Absorption infraroter Strahl. in dünnen Luftschichten. * Met. Z. *54*, 234–242, 1937.
128. —, Ü. d. Absorption v. Wasserdampf u. Kohlens. m. besond. Berücks. d. Druck- u. Temp.abhängigk. * Gerl. B. *54*, 203–234, 1939.
129. Simpson, G. C., Further stud. in terrestrial rad. * Mem. Royal Met. Soc. London *3*, No. 21 1928–30.
130. Steiner, O., Z. Entstehung v. Bodeninvers. bei wolkenlos. Himmel u. Landwind. * Wiss. Abh. d. Rostocker Luftwarte 1926.

Chapter 6. The Warming Process.

130a. Büttner, K. Die Wärmeübertragung durch Leitung und Konvektion, Verdunstung und Strahlung in Bioklimatologie und Meteorologie. * Abh. Pr. Met. I. *10*, Nr. 5, 1934.
130b. Fritsche, G. & Strange, R. Vertikaler Temperaturverlauf über einer Grosstadt. * Beitr. Phys. d. fr. Atm. *23*, 95–110, 136.
131. Geiger, R., Gibt es e. Lufttemp. d. bodenn. Luftschicht? * Biokl. B. *1*, 115–120, 1934.
132. Haude, W., Temp. u. Austausch d. bodenn. Luft über e. Wüste. * Beitr. Phys. d. fr. Atm. *21*, 129–142, 1934.
133. Koch, H. G., Ü. Temp. u. Austausch innerhalb d. Bodeninversion. * Gerl. B. *49*, 407–426, 1937.
134. Malurkar, S. L. & Ramdas, L. A., Theory of extremely high lapse-rates of temp. very near the ground. * Indian J. of Physics *6*, 495–508 (1931?).
135. Raman, P. K., The measurement of the transmission of heat by convect. from isolated ground to the atmosph. * Proc. Indian Acad. Sciences *3*, 98–106, 1936.
136. Ramdas, L. A., The dust-free or dark layer surrounding a hot body in relat. to the convect. movem. in its neighbourhood. * J. Univers. Bombay *6*, 18–22, 1937.
137. Ramdas, L. A. & Malurkar, S. L., Surface convect. and var. of temp. near a hot surface. * Indian J. of Physics *7*, 1–13 (1932?).

138. Ramdas, L. A. & Paranjpe, M. K., An interferometric method of meas. temp. and temp.-gradients very close to a hot surface. * Current Sc. *4*, 642–644, 1936.
139. Robitzsch, M., Einige Bezieh. zw. d. Temp. d. Erdoberfl., d. Insolation u. and. met. Fakt. * Beitr. Phys. d. fr. Atm. *9*, 1–11, 1921.
140. Schmidt, E. & Beckmann, W., D. Temp.-u. Geschwindigk.feld vor. e. Wärme abgeb. senkrecht. Platte bei natürl. Konvektion. * Techn. Mech. u. Thermodynamik *1*, Heft 10/11, 1930.
141. Yakotani, S., On the small fluctuat. of the temp. in the lower atmosph. occurring in the daytime. * J. Met. Soc. Japan *14*, Nr. 2, 1936.
142. Zedler, P., Temp.dauermess. mit e. Aspirationspsychrometer. * Z. f. angew. Met. *55*, 350–353, 1938.

Chapter 7. The Cooling Process.

143. Defant, A., D. nächtl. Abkühl. d. unteren Luftsch. u. d. Erdoberfl. in Abhängigk. v. Wasserdampfgehalt d. Atm. * Sitz-B. Wien. Akad. *125*, 1537–1623, 1916.
144. —, Ü. d. nächtl. Abkühl. d. untersten staubbelad. Luftsch. * Ann. d. Hydr. *47*, 93–105, 1919.
145. —, D. nächtl. Abkühl. d. unt. Luftsch. bei bewegter Luft. * Ann. d. Hydr. *47*, 224–227, 1919.
146. Falckenberg, G., Apparatur z. Best. d. momentanen nächtl. Wärmeaustauschs zw. Erde u. Luft. * Met. Z. *47*, 154–156, 1930.
147. —, D. nächtl. Wärmehaushalt bodenn. Luftsch. * Met. Z. *49*, 369–371, 1932.
148. Krügler, F., Ü. d. Anteil des Massenaustauschs am nächtl. Wärmehaush. d. Erdoberfl. * Met. Z. *49*, 372–376, 1932.
149. Kühnert, W., E. Boeb. d. Temp.grad. beim Auftreten v. Strahl.-nebel; d. Entwickl. d. Bodeninversion. * Beitr. Phys. d. fr. Atm. *18*, 219–224, 1932.
149a. Meyer, E. G., Ü. d. Strahl.haushalt horizont. Flächen. * Gerl. B. *53*, 352–353, 1938.
150. Ramanathan, K. R. & Ramdas, L. A., Derivation of Ångström's formula f. atm. radiation and some general consid. regarding nocturn. cooling of air-layers near the ground. * Proc. Indian. Acad. Sciences *1*, 822–829, 1935.
151. Ramdas, L. A., Frost Hazard in India. * Current Sc. *3*, 325–333, 1935.
152. Ramdas, L. A. & Atmanathan, S., The vert. distrib. of air temp. near the ground during night. * Gerl. B. *37*, 116–117, 1932.
153. Schmauss, A., D. nächtl. Abkühlung d. untersten Luftsch. * Ann. d. Hydr. *47*, 235–236, 1919.
154. Schmidt, Wilh., Stud. z. nächtl. Temp.gang. * Sitz-B. Wien. Akad. *118*, 293–319, 1909.

155. Siegel, S., Mess. d. nächtl. thermischen Gefüges in d. bodenn. Luftsch. * Gerl. B. *47*, 369–399, 1936.
156. Sutton, J. R., On some met. conditions controlling nocturnal radiation. * Transact. Roy. Soc. South Africa *2*, 381, 1912.

Instrumental Technique for the Measurement of Air Temperature in the Microclimate

157. Albrecht, F., Thermometer z. Mess. d. wahren Lufttemp. * Met. Z. *44*, 420–424, 1927.
158. —, Ü. d. Einwirk. d. Strahl. auf frei aufgestellte elektr. Thermometer. * Tät.B. Pr. Met. I. 1933, S. 76–82.
159. Ångström, A., I. Prinzipielles z. Mess. d. Temp. d. Luft. II. Minim. therm. z. Bestimm. d. Min.temp. d. Luft. * Comm. Met. Agricole, Tag-Ber. München 1932, S. 122–127, Utrecht 1933.
160. Bartels, J., Temp.messung in Bodennähe u. Aspiration. * Met. Z. *47*, 76–77, 1930.
161. —, Temp. stabförmiger Versuchskörper. * Z. f. F. u. Jagdw. *68*, 319–327, 1936.
162. Bartels, J. & Köhn, M., Standortsklimat. Unters. in Eberswalde. * Deutsche Forschung *14*, 73–79, 1930.
162a. Brazier, C. E. & Eblé, L., Introduct. à l'étude des temp. de l'air et du sol au voisinage de la surf. terrestre. * La Mét. *10*, 97–110, 1934.
163. Budig, W., Beschirmung v. Bodentherm. gegen nächtl. Ausstrahl. * Erg. d. Met Beob. Potsdam 1915, XI–XVI.
164. Büdel, A., D., Strahl.schutz am Therm. * Z. f. angew. Met. *50*, 225–230, 1933.
164a. Duckert, P., Z. Methode d. Temp.mess. in d. bodenn. Luftschicht. * Comm. Met. Agricole, Tag.Ber. Salzburg 1937, S. 46–53, Leyden 1938.
165. Forster, H., Ü. Fehler, die b. Lufttemp.mess. infolge Wärmeleitung auftreten. * Met. Z. *57*, 334–341, 1940.
166. Gehlhoff, K., Thermoelektr. Mess. d. nächtl. Temp. verlaufs in d. unteren Luftsch. * Met. Z. *39*, 137–141, 1922.
167. Geiger, R., Ein Messgerät z. Dauerbeob. d. Temp.schichtung am Boden. * Z. f. angew. Met. *52*, 205–213, 1935.
168. Geiger, R. & Büdel, A., Ü. ein tragbares Messgerät f. Temp.-bestimm. in d. bodenn. Luftsch. * Z. f. angew. Met. *46*, 265–270, 1929.
169. Gründl, G., Erfahr. mit Sechsfarben-Punktschreibern b. widerstandselektr. Temp.mess. * Met. Z. *56*, 230–239, 1939.
170. Grundmann, W. & Kassner, L., E. vereinf. elektr. Temp.-messanordnung f. beliebig viele Messstellen u. mehr. Temp. bereiche. * Z. f. angew. Met. *51*, 205–210, 1934.
171. Linke, F., E. transport. Therm-hütte f. lokalklimat. u. mikroklimat. Unters. * Bioklim. B. *5*, 110, 1938.

172. —, Ü. d. Genauigk. d. Temp.mess. mit d. Sechsfach-Punktschreibern d. Fa. Hartmann & Braun. * Met. Z. 57, 263–265, 1940.
173. Mäde, A., E. Beitrag z. Frage: Wahre Lufttemp. oder Versuchskörpertemp. * Biokl. B. *4*, 35–36, 1937.
174. —, E. Schutzkorb für d. Platinwiderst.therm. d. Reichswetterdienstes. * Met. Z. 55, 415–417, 1938.
174a. Ramdas, L. A., Rep. on simple methods of measur. in agricult. met. * Comm. Met. Agricole, Tag.Ber. Salzburg 1937, S. 53–57, Leyden 1938.
175. Schmidt, Wilh., Ventilation b. Temp.mess. schädlich? * Met. Z. 51, 431–432, 1934.
175a. Wertheimer, E. D., Temp.begriff in d. Thermodynamik u. in d. Met. * Met. Z. *45*, 457–465, 1928.

Chapters 8 and 9. The Diurnal and Annual Course of Temperature in the Air Layer near the Ground and the Temperature Gradient in the Air Layer Near the Ground.

176. Best, A. C., Transfer of heat and momentum in the lowest layers of the atmosphere. * Geophys. Mem. Nr. 65, London 1935.
177. Favrot, C., Sur les min. de temp. au-dessus du sol à Lyon-Bron. * La Mét. *6*, 206–209, 1930.
178. Flower, W. D., An invest. into the variation of the lapse rate of temp. in the atm. near the ground at Ismailia, Egypt. * Geophys. Mem. Nr. 71, London 1937.
179. Geiger, R., Das Stationsnetz zur Unters. d. bodenn. Luftsch. Teil I–III. * Deutsch. Met. Jahrb. f. Bayern 1923–1925.
180. Geiger, R. &. Amann, H., dasselbe, Teil IV u. V. * Ibid. 1926–1927.
181. Heyer, E., Ü. Frostwechselzahlen in Luft u. Boden. * Gerl. B. 52, 68–122, 1938.
182. Johnson, N. K., A Study of the vertical gradient of temp. in the atm. near the ground. * Geophys. Mem. Nr. 46, London 1929.
183. Johnson, N. K. & Roberts, O.F.T., The measurement of the lapse rate of temp. by an optical method. * Quart. J. *51*, 131–138, 1925.
184. Kähler, K., Mess. d. Lufttemp. in verschied. Höhe auf der Schneekoppe. * Tät-B. Pr. Met. I. 1910, S. 123–128.
184a. Karsten, H., Beitr. z. Kenntnis d. Temp.verhältn. in d. untersten Luftsch. * Arb. d. finn. landw.-ökonom. Vers.Anst. Helsingfors 1921.
185. Knoch, K., E. Beitrag z. Kenntn. d. Temp.- u. Feucht.verhältn. in verschied. Höhe ü. d. Erdboden. * Abh. Pr. Met. I. *3*, Nr. 2, 1909.
186. Mäde, A., Mess. mit. Widerstandsthermom. an Funktürmen. * Beitr. Phys. d. fr. Atm. *21*, 309–312, 1934.
187. —, Widerstandselektr. Temp.beob. an e. mikroklimat. Basisstation. * R. f. W. Wiss. Abh. *4*, Nr. 3, 1938.

187a. Mal, S., Desai, B. N., and Sircar, S. P. An investigation into the variation of the lapse rate of temperature in the atmosphere near the ground at Drigh Road, Karachi. * Memoirs India Met. Dep. XXIX, Part 1, Calcutta, 1942.
188. Mörikofer, W., La temp. de l'air dans la couche d'un mètre d'épaisseur au-dessus du sol. * C. R. de la séance Soc. Suisse de Géophys., Mét. et Astr. 1921.
189. Novak, V., D. vertikale Verteilung d. Temp.extreme bei ungesch. Extremtherm. i. d. bodenn. Luftsch. * Sbornik csl. Akad. zemed. Prag. *10*, 537–545, 1935.
190. de Quervain, F. & Gschwind, M., D. nutzbaren Gesteine d. Schweiz. * Bern, Verlag H. Huber, 1934.
191. Ramdas, L. A., Kalamkar, R. J. & Gadre, K. M., Agricultural Met. Stud. in micro-climat. * Indian J. of Agric. Sc. *4*, 451–467, 1934.
192. ——, the same, Pt II. * Ibid. 5, 1–11, 1935.
193. Schmidt, Wilh., Ü. d. tägl. Temp.gang in d. unteren Luftsch. * Met. Z. *37*, 49–59, 1920.
194. Seltzer, P., Sur la répartition verticale de la temp. de l'air dans les 2 prem. mètres au-dessus du sol. * C. R. Paris *196* (II), 1626–1628, 1933.
195. Slanar, H., Klimabeob. aus Zentral-Island. * Met. Z. *50*, 379–383, 1933.
196. Steinhauser, F., Temp.schichtung u. Windstruktur in Bodennähe. * Met. Z. *52*, 439–443, 1935.
196a. Troll, C., Die Frostwechselhäufigkeit in den Luft- und Bodenklimaten der Erde. * Met. Z. *60*, 161–171, 1943.
196b. —, Die Formen der Solifluktion und die periglaziale Bodenabtragung. * Erdkunde *1*, 162–175, 1947.
197. Vujevic, P., D. Temp.verhältn. d. untersten Luftsch. * Sitz-B. Wien. Akad. *118*, 971–1018, 1909.
198. Woeikof, A., Temp. d. untersten Luftsch. * Met. Z. *21*, 49–50, 1904.

Chapter 10. Humidity Relationships.

(See also the bibliography for Chapters 8 and 9 and for the Supplement to Part 1)

199. Büdel, A., D. Feucht.messung in d. bodennahen Luftschicht. * Z. f. angew. Met. *48*, 289–293, 1931.
200. Buxton, P. A., The measurement and control of atm. humidity in relation to entomolog. problem. * Bull. Entomolog. Res., London *22*, 431–447, 1931.
201. Buxton, P. A. & Mellanby, K., The measurement and control of humidity. * Ibid. *25*, 171–175, 1934.
202. Defant, A., Zum tägl. Gang d. relat. Feucht. * Met. Z. *32*, 61–69, 1915.

202a. Dörffel, K. & Lettau, H., Der Wasserdampfübergang von einer nassen Platte an strömende Luft. * Ann. d. Hydr. *64*, 342–352, 504–510, 1936.
203. Hamberg, H. E., La temp. et l'humid. de l'air à diff. hauteurs, observées à Upsal pendant l'été de 1875. Upsala 1876.
204. Hill, S. A., On temp. and humidity observ. made at Allahabad at various heights above the ground. * Indian Met. Mem. Calcutta *4*, 361–394, 1889.
205. Howell, D. E. & Craig, R., A small hygrometer. * Science *89*, 544, 1939.
205a. Huber, Br., Versuche zur Messung des Wasserdampf-und Kohlendioxyd-Austausches über Pflanzenbeständen. * Sitz- B. Wien. Akad. *155*, 97–145, 1947.
206. Koch, W., Mess. d. Luftfeucht. mit Thermoelementen ohne künstl. Belüftung. * Gesundheits-Ingenieur *59*, 504–505, 1936.
207. Möller, F., Ü. d. tägl. Gang d. Dampfdrucks u. s. interdiurnen Veränderlichk. * Met. Z. *54*, 124–133, 1937.
208. Nielsen, E. T. & Thamdrup, H. M., E. Hygrometer f. mikroklimat. Untersuch. * Biokl. B. *6*, 180–184, 1939.
208a. Prügel, H., Zum Problem der Nebelverstärkung und -auflösung nach Sonnenaufgang. * Ann. d. Hydr. *71*, 420–422, 1943.
209. Ramdas, L. A., The variation with height of the water vapour content of the air layers near the ground at Poona. * Biokl. B. *5*, 30–34, 1938.
210. Ramdas, L. A. & Katti, M. S., Preliminary stud. on soil-moisture in relation to moisture in the surface layers of the atm. during the clear season at Poona. * Indian J. of Agric. Sc. *4*, 923–937, 1934.
211. Rossi, V., Ü. mikroklimat. Temp. u. Feucht.beob. mit Thermoelementpsychrometern. * Soc. Scient. Fennica; Comm. Phys. Math. *6*, Nr. 25, 1–22, 1933.
212. Smolik, L., D. rel. Feucht. d. Luft nächst d. Bodenoberfl. * Sbornik csl. akad. zemed. Prag *10*, 98–103, 1935.
213. Szymkiewicz, D., Ökolog. Unters. im Torfmoor Czerme I. Brześc 1931.
213x. Thornthwaite, C. W. & Holzman, B., The determination of evaporation from land and water surfaces. * M. W. Rev. *67*, 4–11, 1939.
213a. Wald, H., E. Psychrometer ohne künstl. Belüftung. * Z. f. d. ges. Kälte-Industrie *39*, Heft 6, 1932.

Chapter 11. Wind Relationships

214. Albrecht, F., E. Messgerät z. Mess. u. Registr. kleiner Windgeschw. u. s. Anwendung auf d. Unters. d. Wärmeumsatzes an d. Erdoberfl. * Met. Z. *47*, 465–474, 1930.

215. Ali, B., Variation of wind with height. * Quart. J. *58*, 285–288, 1932.
215a. Bagnold, R. A., The measurement of sand storms. * Proc. Roy. Soc. London *167*, 282–291, 1938.
215b. Carruthers, N., Variations in wind velocity near the ground. * Quart. J. *69*, 289–301, 1943.
216. Hellmann, G., Ü. d. Bewegung d. Luft in d. untersten Schichten d. Atm. * Met. Z. *32*, 1–16, 1915.
217. —, Ü. d. Beweg. d. Luft in d. untersten Sch. d. Atm. * Sitz-B. Berlin. * Akad. 1919, 404–416.
218. Heywood, G. S. P., Wind structure near the ground and its relation to temp. gradient. * Quart. J. *57*, 433–452, 1931.
219. Katheder, F., Auflösung e. Bodennebeldecke d. e. startendes Flugzeug. * Z. f. angew. Met. *54*, 61–63, 1937.
220. Knoch, K., Lebhafte Schwank. d. Temp. an d. Grenzfläche d. untersten Bodeninversion. * Tät-B. Pr. Met. I. 1909, S. 113–124.
221. Köhler, H., E. kurzes Studium d. Austauschs auf Grund d. Potenzgesetzes. * Beitr. Phys. d. fr. Atm. *19*, 91–104, 1932.
222. McAdie, A. G., Studies in frost protection — effect of mixing the air. * M. W. Rev. *40*, 122–123, 779, 1912.
223. Mierdel, F., Ü. nächtl. Temp.anstiege an d. Möhne-Talsperre. * Met. Z. *40*, 178, 1923.
224. Paeschke, W., Experimentelle Unters. z. Rauhigkeits- u. Stabil.-problem in d. bodenn. Luftsch. * Beitr. Phys. d. fr. Atm. *24*, 163–189, 1937.
225. Peppler, A., Windmess. auf d. Eilveser Funkenturm. * Beitr. Phys. d. fr. Atm. *9*, 114–129, 1921.
226. Prandtl, L., Met. Anwendung d. Strömungslehre. * Beitr. Phys. d. fr. Atm. *19*, 188–202, 1932.
227. Prandtl, L. & Tollmien, W., D. Windverteilung über d. Erdboden, errechnet a. d. Gesetz d. Rohrströmung. * Z. f. Geophysik *1*, 47–55, 1924/25.
228. Schmidt, Wilh., D. Windgeschw. in Bodennähe. * Met. Z. *36*, 88–90, 1919.
229. —, Unters. ü. d. Feinbau d. Windes. * Deutsche Forschung *14*, 54–66, 1930.
230. Stevenson, Th., Rep. on simultaneous observ. of the force of wind at diff. heights above the ground. * J. Scottish Met. Soc. *5*, 348–351, 1880.
231. Sutton, O. G., Note on the variation of the wind with height. * Quart. J. *58*, 74–76, 1932.
232. Sverdrup, H. U., Second note on the logar. law of wind structure near the ground. * Quart. J. *65*, 57–60, 1939.
233. Viereck, W., Reg.gerät f. geringe Windgeschw. * Met. Z. *50*, 426–428, 1933.

234. Wagner, A., Zur Theorie d. tägl. Ganges d. Windverhältn. * Gerl. B. *47*, 172–202, 1936.
235. Young, F. D., Notes on the 1922 freeze in southern California. * M. W. Rev. *51*, 581–585, 1923.

Chapter 12. Optical and Acousticai. Phenomena. Content of Dust, Carbon Dioxide and Emanation.

236. Auer, R., Ü. d. tägl. Gang d. Ozongehalts d. bodenn. Luft. * Gerl. B. *54*, 137–145, 1939.
237. Aujeszky, L., Kleinklima u. Schallklima. * Forsch. u. Fortschr. *14*, 413–415, 1938.
238. Becker, F., Mess. d. Emanationsgeh. d. Luft in Frankf. a. M. u. am Taunusobserv. * Gerl. B. *42*, 365–384, 1934.
239. Bielich, F. H., Einfluss d. Grosstadttrübung a. Sicht. u. Sonnenstrahl. * Veröff. Geophys. I. Leipzig *6*, Heft 2, 1933.
239a. Bigg, W. H., Road mirages. * Met. Mag. *63*, 138, 1928.
240. Braak, C., Luchtspieg. en verwante versch. in ons Polderland. * Tijdschr. K. Nederl. Aardr. Gen. *39*, 587, 1922.
240x. Buch, K., Kohlensäure in Atmosphäre und Meer. * Ann. d. Hydr. *70*, 193–205, 1942.
240y. Cauer, H., Öl und ölhaltige Bestandteile in der Luft. * Angew. Chemie *53*, 171–172, 1940.
240a. Dufour, L., Des temps. de l'air et des mirages à la surface du lac Léman. * Bull. Soc. vand. sc. nat. Lausanne 5, 26, 1858.
240b. Effenberger, E. F., Kern- und Staubuntersuchungen am Collmberg. * Veröff. Geoph. I. Leipzig *12*, Heft 5, 1940.
241. Findeisen, W., Ü. Beob. v. Luftspiegel. auf d. Neuwerker Watt. * Ann. d. Hydr. *62*, 423–426, 1934.
242. Futi, H., On road mirage. * Geophys. Mag. Tokio *4*, 387, 1931.
242a. Gish, O. H., The distrib. of electric elements in the atm. near the earth's surface. * Transact. Americ. Geophys. Union 1940, S. 314–316.
243. Goldschmidt, H., Mess. d. atmosph. Trübung mit e. Scheinwerfer. * Met. Z. 55, 170–174, 1938.
243a. Hartmann, W., Erdbodennahe Haloerscheinungen. * Met. Z. *46*, 269–270, 1929.
244. Hofmann, A., Fata Morgana in d. Rheinprovinz. * Met. Z. *52*, 29–30, 1935.
245. Israel-Köhler, H., Aufg. u. Ziele d. Boden-Emanationsforschung. * Balneologe 5, 248–260, 1938.
246. Jones, T. W. V., Road mirages. * Met. Mag. 62, 261–262, 1927.
247. Köppen, W., D. Eigenart d. untersten Luftschicht. * Beitr. Phys. d. fr. Atm. *15*, 205–209, 1929.
247a. Kreutz, W., Kohlensäuregehalt der unteren Luftschichten in Abhängigkeit von Witterungsfaktoren. * Angew. Bot. *23*, 89–117, 1941.

248. Kohlhörster, W., D. Erdstrahl. auf d. Gelände d. Met.-Magnet. Observ. Potsdam. * Met. Z. *56*, 35–38, 1939.
249. Lehmann, G., Blitze, Wasseradern u. Wünschelrute. * Met. Z. *49*, 284–285, 1932.
250. Meissner, O., D. Gripeepidemie 1939 u. d. Wetter. * Biokl. B. *7*, 42–43, 1940.
251. Miyanisi, M., On the mysterious sea fire "Siranui" in Japan. * Sc. Pap. Inst. Phys. and Chem. Res. *36*, 198–243, 1939.
252. Musso, J. O., Spann.erhöhung d. elektr. Feldes mittels Mulchierung d. Bodens. * Biokl. B. *1*, 21–25, 1934.
253. Musso, J. O., E. mögl. Zus.hang zw. d. Grad. d. elektr. Feldes, d. Agrotechnik u. d. Ernte. * Biokl. B. *3*, 30–35, 1936.
254. Pernter, J. M. & Exner, F. M., Meteorolog. Optik. Wien & Leipzig, W. Braunmüller, 1922.
254a. Portig, W., Halo im Eisnebel. * Met. Z. *59*, 207–208, 1942.
255. Priebsch, J., D. Höhenverteilung radioakt. Stoffe in d. fr. Luft. * Met. Z. *49*, 80–81, 1932.
255a. Romage, A. G., Mirage on the Queensferry road. * Proc. Roy. Soc. Edinburgh *38*, 166–168, 1917/18.
256. Ramdas, L. A. & Malurkar, S. L., Theory of extremely high lapse rates of temp. very near the ground. * Indian J. of Physics *6*, 495–508, 1932.
256a. Rötschke, M., Untersuchungen über die Meteorologie der Staubatmosphäre. * Veröff. Geophys. I. Leipzig *11*, Heft 1, 1937.
257. Schiele, W. E., Z. Theorie d. Luftspiegelungen. * Veröff. Geoph. I. Leipzig 7, Heft 3, 1935.
258. Schmid-Curtius, C., Heilklimat. Untergrunds- u. Waldluftforsch. i. nordwestl. Thüringer W. * Z. f. angew. Met. *46*, 161–175, 194–201, 233–241, 257–262, 1929.
258a. Scott, Captain, Letzte Fahrt I. * Brockhaus Leipzig 1913.
259. Vedy, L. G., Sand mirages. * Met. Mag. *63*, 249–253, 1928.
259a. Wegener, A., Optik der Atmosphäre. * Müller-Pouillets Lehrbuch der Physik V, 1. Hälfte (11. Aufl.) 1928.

Chapter 13. The Temperature of the Ground Surface.

260. Ångström, A., The albedo of various surfaces of ground. * Geograf. Ann. 7, 323–342, 1925.
260a. Bac, S., Schwankungen der Bodenschichten infolge Gefrierens und Auftauens. * 6. Balt. Hydr. Konf. Berlin 1938.
261. Bartels, J., D. Strahlung u. ihre Bedeut. f. d. Klima. * Z. f. F. u. Jagdw. *62*, 537–563, 1930.
262. Brooks, C. F., Parade-ground temp. at College Stat, Tex. * M. W. Rev. *47*, 801, 1919.
263. Brückmann, W., Ü. Vers. d. Registr. d. Oberfl.temp. d. Bodens mit elektr. Therm. * Tät-B. Pr. Met. I. 1917–1919, S. 111–116.

264. Büttner, K., Mess. d. Sonnen- u. Himmelsstrahl. i. Flugzeug. * Met. Z. *46*, 525–527, 1929.
265. Diem, M., Bodenatmung. Messtechnik u. Ergebn. * Gerl. B. *51*, 146–166, 1937.
266. Dorno, C., Ü. d. Erwärmung v. Holz unter verschied. Anstrichen. * Gerl. B. *32*, 15–24, 1931.
266a. Dücker, A., Der Bodenfrost im Strassenbau. * "Der Verkehr," Schulz-Wittuhn Bd. 2. F. Schmidt-Verlag, Berlin and Detmold 1947.
267. Dufton, A. F. & Beckett, H. E., Terrestrial temp. * Met. Mag. *67*, 252–253, 1932.
268. Eaton, G. S., High relat. temp. of pavement surfaces. * M. W. Rev. *47*, 801–802, 1919.
269. Falckenberg, G., Absorptionskonst. einig. met. wichtiger Körper f. infrarote Wellen. * Met. Z. *45*, 334–337, 1928.
270. —, Apparat z. Mess. d. Himmelsstrahl. u. Bodentemp. * Met. Z. *45*, 422–425, 1928.
271. Fleischmann, R., Beob. ü. d. Auffrieren d. Bodens. * Fortschr. d. Landwirtsch. *6*, 673–685, 1931.
272. —, Vom Auffrieren d. Bodens. * Biokl. B. *2*, 88–90, 1935.
273. Hausmann, W. & Kuen, F. M., Ü. d. biolog. Wirkung der von Oberflächen verschied. Natur reflekt. ultravioletten Strahlung. * Wiener klin. Wochenschr. 1934, Nr. 24.
273a. Penman, H. L., Daily and seasonal changes in the surface temperature of fallow soil at Rothamsted. * Quart. J. *69*, 1–16, 1943.
274. Ramanathan, K. R., On temp. of exposed rails at Agra. * India Met. Dep. Scientific Notes *1*, Nr. 4, 1929.
274a. Ramdas, L. A. & Dravid, R. K., Soil temp. * Current Sc. *3*, 266–267, 1934.
274b. Reeder, G., Ground temp. compared with air temp. in a shelter. * M. W. Rev. *48*, 637–639, 1920.
275. Richardson, L. F., The reflectivity of woodland, fields and suburbs between London a. St. Albans. * Quart. J. *56*, 31–38, 1930.
276. Ritscher, A., D. Deutsche Antarkt. Exped. * Ann. d. Hydr. *67*, Beiheft zu VIII, 9–19, 1939.
277. Rücker, F., Ü. d. Ultrarotreflexion tierischer Körperoberfl. * Z. f. vergl. Physiologie *21*, 275–280, 1935.
277a. Schanderl, H. & Weger, N., Stud. über d. Mikrokl. vor verschiedenfarb. Mauerflächen u. d. Einfl. auf Wachstum u. Ertrag v. Tomaten. * Biokl. B. *7*, 134–142, 1940.
278. Schmauss, A., Ein d. Erdwurf ähnl. Schneewurf. * Met. Z. *55*, 380, 1938.
279. Schmidt, Wilh., E. neues Verfahren z. Messung d. Bodentemp. * Z. f. Instrum.kde *46*, 431–433, 1926.
280. Schmidt, Wilh. & Lehmann, P., Vers. zur Bodenatmung. * Sitz-B. Wien. Akad. *138*, 823–852, 1929.

281. Schropp, K., D. Temp. techn. Oberflächen unter d. Einfluss d. Sonnenbestrahl. u. d. nächtl. Ausstrahl. * Gesundh.-Ing. 1931, S. 729–736.
282. Voigts, H., Strahl.-u. Rückstrahl.mess. mit Hilfe d. photograph. App. in Travemünde. * Biokl. B. *1*, 128–133, 1934.
283. —, Das UV-Klima d. Lübecker Bucht. * Biokl. B. *4*, 72–77, 1937 und 5, 20–22, 1938.
284. Vujevic, P., D. Temp. verschiedenart. Bodenoberfl. * Met. Z. *29*, 570–576, 1912.
285. Wollny, E., Unters. ü. d. Einfluss d. Farbe des Bodens auf dessen Erwärmung. * Forsch. a. d. Geb. d. Agrik.physik *1*, 43–69, 1878.

CHAPTER 14. THE INFLUENCE OF THE TYPE AND CONDITION OF THE SOIL.
(See also the bibliography for Chapter 3)

286. Bălănică, T., Beitr. z. e. Met. d. Bodens. Diss. München, Bukarest 1940.
287. Becker, F., D. Erdbodentemp. als Indikator d. Versickerung. * Met. Z. *54*, 372–377, 1937.
288. Firbas, F., Ü. d. Bedeutung d. therm. Verhaltens d. Laubstreu für d. Frühjahrsvegetation d. sommergrünen Laubwaldes. * Beih. z. Botan. Centralbl. *44*, Abt. II, 179–198, 1927.
289. Fuchs, O., Bodenwasser u. therm. Konvektion. * Beitr. Phys. d. fr. Atm. *20*, 174–213, 1933.
290. Geiger, R. & Fritzsche, G., Spätfrost u. Vollumbruch. * Forstarchiv *16*, 141–156, 1940.
291. Homén, T., Bodenphysikal. u. met. Beob. mit besond. Berücksicht. d. Nachtfrostphänomens. * Berlin 1894.
292. Johnson, N. K. & Davies, E. L., Some measurements of temp. near the surface in various kinds of soils. * Quart. J. *53*, 45–59, 1927.
293. Keen, B. A., Soil physics in relation to meteorology. * Quart. J. *58*, 229–250, 1932.
294. Keil, K., Temp.erhöhung d. Erdbodens bei Bränden. * Z. f. angew. Met. *57*, 26–27, 1940.
295. Keränen, J., Ü. d. Bodenfrost in Finnland. * Mitt. d. Met. Zentralanst. d. finn. Staats Nr. 12, 1923.
296. Krauss, G. Müller, K. & Gärtner, G., Standortsgemässe, Durchführ. d. Abkehr von d. Fichtenwirtschaft im nordwestsächsischen Niederland. * Thar. Forstl. Jahrb. *90*, 481–715, 1939.
296a. Kreutz, W., Das Eindringen des Frostes in Böden unter gleichen und verschiedenen Witterungsbedingungen während des sehr kalten Winters 1939/40. * R. W. Wiss. Abh. *9*, Nr. 2, 1942.
296b. —, Beitrag zur Erforschung des Boden- und bodennahen Klimas im Emslandmoor etc. * Z. f. Landwirtsch. *81*, 81–112, 1943.
296c. —, Der Jahresgang der Temperatur in verschiedenen Böden unter gleichen Witterungsverhältnissen. * Z. f. angew. M. *60*, 65–76, 1943.

297. Kreutz, W. & Rohweder, M., Korrel.-analyse d. Temp.- u. Feucht. verlaufs in extrem verschied. Böden u. in d. bodennahen Luft. * R. F. W. Wiss. Abh. *1*, Nr. 9, 1936.
298. Lauscher, F., Mikroklimat. Temp.beob. an e. Wintertag im Gebirge. * Biokl. B. *5*, 65–66, 1938.
298a. Lehmann, P., E. Vorschlag z. Kontrolle d. Bodenegalität beim Veg.versuch. * Fortschr. d. Landwirtsch. 7, 247–253, 1932.
299. Mayer, H., Beob. ü. d. Wärmeleitfähigkeit. * Synopt. Bearb. d. Frankfurter Wetterd.st. Linke-Sonderheft, 1933, S. 67.
300. Ramdas, L. A. & Dravid, R. K., Soil temperatures. * Current Sc. *3*, 266–267, 1934.
301. Ramdas, L. A. & Katti, M. S., Stud. on soil-moisture in relation to moisture in the surface layers of the atm. during the clear season at Poona. * Indian J. of Agric. Sc. *6*, 1163–1200, 1937.
301a. Schmauss, A., Kleinklimabeob. ohne Instr. * Z. f. angew. Met. *57*, 401–402, 1940.
301b. —, Kleinklimabeobachtungen ohne Instrumente. * Wetter u. Klima *1*, 27–36, 1948.
302. Schmidt, Wilh., Ü. kleinklimat. Forsch. * Met. Z. *48*, 487–491, 1931.
303. Scultetus, H. R., D. Beob. d. Erdbodentemp. im Beob.netze d. Pr. Met. I. während d. Jahre 1912–1927. * Abh. Pr. Met. I, 9, Nr. 5, 1930.
303a. Slanar, H., Schneeabschmelzungen im bewachsenen Gelände. * Met. Z. *59*, 413–416, 1942.
304. Vujevic, P., Ü. d. Bodentemp. in Belgrad. * Met. Z. *28*, 289–301, 1911.
304a. Wild, H., Ü. d. Diff. d. Bodentemp. mit u. ohne Veget.- bzw. Schneedecke. * Mem. Akad. Petersburg *8*, 1897.
305. Wollny, E., Unters. ü. d. Einfluss d. oberfl. Abtrocknung d. Bodens auf d. Temp.- u. Feucht.verhältn. * Forsch. a. d. Geb. d. Agrik. physik *3*, 325–348, 1880.
305a. Yakuwa, R., Ü. d. Bodentemp. in d. verschied. Bodenarten. * Geophys. Mag. Tokio *6*, 179–187, 1932.

Chapter 15. The Air Layer over Water.

306. Ångström, A. & Jacobson, S., Temp. mätningar i Vänern och Götaälv. * Medd. Stat. Met. Hydr. Anst. Stockholm *7*, Nr. 6, 1940.
306a. Bruch, H., Die vertikale Verteilung von Windgeschwindigkeit und Temperatur in den untersten Metern über der Wasseroberfläche. * Veröff. I. f. Meereskunde Berlin Neue F. A. H. 38. 1940.
307. Büttner, K. & Sutter, E., D. Abkühl.grösse in d. Dünen. Rückstrahl. verschied. Bodenbedeck. f. uv. u. gesamte Sonnenstrahl. * Strahlentherapie *54*, 156–173, 1935.

308. Conrad, V., Oberfl.-Temp. in Alpenseen. * Gerl. B. *46*, 44–61, 1935.
309. —, Z. Wasserklima einiger alpiner Seen Österr. * Beih. z. Jahrb. d. Zentralanst. f. Met. Wien Jahrg. 1930, Wien 1936.
309a. Defant, A., Der Einfluss des Reflexionsvermögens von Wasser und Eis auf den Wärmeumsatz der Polargebiete. * Veröff. D. Wiss. Inst. zu Kopenhagen, Reihe I (Arktis) Nr. 5, 1942.
310. Dietrich, G., D. Absorption d. Strahl. im reinen Wasser u. im r. Meerwasser. * Ann. d. Hydr. *67*, 411–417, 1939.
311. Exner, F. M., Mess. d. tägl. Temp.schwank. in verschied. Tiefen d. Wolfgangsees. * Sitz-B. Wien. Akad. *109*, 905–922, 1900.
312. Findeisen, W., Ü. Beob. auffäll. Wellenbildung auf dünner Wasserschicht auf d. Neuwerker Watt. * Ann. d. Hydr. *63*, 186–189, 1935.
313. Frey, H., D. Frühlingseinzug am Zürichersee. * Neujahrsbl. 1931, her. . d. Naturf. Ges. Zürich *133*, 1–48, 1931.
314. Herzog, J., Thermische Unters. in Waldteichen. * Veröff. Geoph. I. Leipzig *8*, Heft 2, 1936.
315. Kleinschmidt, E., Beitr. z. Limnologie d. Bodensees. * Schr. d. Ver. f. Geschichte d. Bodensees *49*, 1921.
316. Kuhlbrodt, E. & Reger, J., Die met. Beob. in "Wissensch. Erg. d. Deutsch. Atl. Exped. a. d. Meteor 1925–27" *14*, Berlin 1938.
317. Marquardt, R., Unters. d. Wärme- u. Wasserdampfaustauschs über d. Bodensee. * Gerl. B. *36*, 78–132, 1932.
318. Merz, A., D. Oberflächentemp. d. Gewässer. * Veröff. Inst. f. Meereskde Berlin, neue Folge 5, 1920.
318a. Model, F., Die Rauhigkeit der Meeresoberfläche. * Gerl. B. *59*, 102–142, 1942.
319. Peppler, W., Langjähr. Mittelwerte d. Temp. d. Luft u. d. Wassers am Bodensee in d. frühen Morgenstunden. * Wetter *43*, 205–207, 1926.
320. —, Beitr. z. Kenntn. d. Oberfl.temp. d. Bodensees. * Z. f. angew. Met. *44*, 250–256, 1927 and *45*, 14–20, 99–105, 1928.
321. —, Temp. d. Wassers u. d. Luft auf d. Bodensee. * R. f. W. Wiss. Abh. *3*, Nr. 7, 1937.
322. Pichler, W., Temp.mess. an e. Tümpel. * Biokl. B. *4*, 25–27, 1937.
323. —, Sind d. Verlandungszonen d. Seen in ihrer Thermik Kleingewässern v. entsprech. Tiefe ökologisch gleichwertig? * Biokl. B. *5*, 107–109, 1938.
324. —, D. Almtümpel als Lebensstätte. * Biokl. B. *6*, 85–89, 1939.
324a. Roll, U., Zur Frage des täglichen Temperaturgangs und des Wärmeaustausches in den unteren Luftschichten über dem Meere. * Aus d. Archiv d. Seewarte *59*, Nr. 9 Hamburg 1939.
325. Sauberer, F., Ü. d. Lichtverhältn. d. Binnenseen. * Biokl. B. *6*, 33–41, 1939.

326. Schmidt, Wilh., Ü. d. Reflexion d. Sonnenstrahlung an Wasserflächen. * Sitz-B. Wien. Akad. *117*, 75–89, 1908.
326a. —, Absorption d. Sonnenstr. im Wasser. * Ibid. *117*, 237–253, 1908.
327. —, Über Boden- u. Wassertemp. * Met. Z. *44*, 406–411, 1927.
328. —, Ein Jahr Temp.mess. in 17 österr. Alpenseen. * Sitz-B. Wien. Akad. *143*, 431–452, 1934.
328b. Volk, O. H., Ein neuer für botanische Zwecke geeigneter Lichtmesser. * Ber. D. Bot.-G. 52, 195–202, 1934.
329. Wüst, G., Temp. u. Dampfdruckgefälle in d. untersten Metern ü. d. Meeresoberfläche. * Met. Z. *54*, 4–9, 1937.

Chapter 16. The Air Layer near Snow.

330. Ångström, A., On the radiation and temp. of snow and the convection of the air at its surface. * Ark. f. Mat. *13*, Nr. 21, 1919.
331. —, D. Einfluss d. Bodenoberfläche auf d. Lichtklima. * Gerl. B. *34*, 123–130, 1931.
331a. Diem, M., Schneeforschung. * Naturwiss. *32*, 12–20, 1944.
331b. —, Messungen an einer Scheedecke. * Z. f. angew. Met. *61*, 37–50, 1944.
332. Eckel, O. & Thams, Ch., Unters. ü. Dichte, Temp. u. Strahl.-verhältn. d. Schneedecke in Davos. * Geologie d. Schweiz, Hydrologie Lief. 3, 275–340, 1939.
333. Gabran, O., D. Luftdurchlässigk. e. Schneedecke u. deren Einfluss auf d. Überwinterung d. Pflanzen. * Met. Z. *56*, 354–356, 1939.
333a. Georgi, J., Die bodennahe Luftschicht über dem grönländischen Eis. * Veröff. Deutsch. Wiss. Inst. Kopenhagen I, 11, 1943.
334. Götz, P., D. Strahl.klima von Arosa. Berlin 1926.
335. Geiger, R., D. Schutz d. Kulturen durch e. Schneedecke. * Forstw. C. *58*, 105–114, 1936.
336. Horton, R. E. & Leach, H. R., Snow-surface temp. * M. W. Rev. *62*, 128–130, 1934.
337. Juhlin, J., Sur la temp. nocturne de l'air à diff. hauteurs. Upsala 1890.
338. Kalitin, N. N., D. Strahl.eigensch. d. Schneedecke. * Gerl. B. *34*, 354–366, 1931.
339. Keränen, J., Ü. d. Temp. d. Bodens u. d. Schneedecke in Sodankylä. Helsinki 1920.
340. Korhonen, W. W., Ü. d. lokale Veränderlichk. d. Schneedecke. * Met. Z. *49*, 72–76, 1932.
340a. Kreutz, W., Schutzwirkung einer Schneedecke. * Z. f. angew. Met. *58*, 305–314, 1941.
341. Lauscher, F. & Eckel, O., Z. Kenntnis d. Winterklimas d. Kanzelhöhe. * Mitt. d. Volksgesundh.Amts Wien 1931, Heft 6/7.
341a. Levi, F. & Chorus, U., Wintertemp. in u. unter d. Schneedecke. * Verh. d. Schweiz. Naturf. Ges. *113*, 319, 1932.

342. Lindholm, F., Beitrag z. polaren Lichtklima. * Biokl. B. *5*, 26–30, 1938.
342a. Löhle, F., Absorptionsmessungen an Neuschnee und Firnschnee. * Gerl. B. *59*, 283–298, 1943.
343. Michaelis, P., Ökolog. Studien an d. alpinen Baumgrenze: I. D. Klima u. d. Temp.verhältn. d. Vegetationsorgane im Hochwinter. * Ber. D. Bot. G. *52*, 31–42, 1932.
343a. —, — —, II. D. Schichtung d. Windgeschw., Lufttemp. u. Evaporation über e. Schneefläche. * Beih. z. Botan. Centralbl. *52*, 310–332, 1934.
344. —, — —, V. Osmot. Wert u. Wassergehalt während d. Winters in d. verschied. Höhenlagen. * Jahrb. f. wiss. Bot. *80*, 337–362, 1934.
345. Nyberg, A., Temp. measurements in an air layer very close to a snow surface. * Geograf. Ann. *20*, 234–275, 1938.
346. Olsson, H., Radiation measur. on Isachsen's Plateau. * Geograf. Ann. *18*, 225–244, 1936.
347. Paulcke, W., Prakt. Schnee- u. Lawinenkunde. * Berlin, Julius Springer, 1938.
348. Rossmann, F., Beob. ü. Schneerauchen u. Seerauchen. * Z. f. angew. Met. *51*, 309–317, 1934.
349. —, D. Schnee d. Schiläufers. * Z. f. angew. Met. *51*, 382–391, 1934.
350. Sauberer, F., Vers. ü. spektrale Mess. d. Strahl.eigenschaften v. Schnee u. Eis mit Photoelementen. * Met. Z. *55*, 250–255, 1938.
351. Sverdrup, H. U., Diurnal variation of temp. at polar stations in spring. * Gerl. B. *32*, 1–14, 1931.
352. Thams, Ch., Ü. d. Strahl.eigenschaften d. Schneedecke. * Gerl. B. *53*, 371–388, 1938.
353. Tolsky, A., Ü. d. Temp. d. Schneedecke. * Geophys. u. Met. Z. in Russland *2*, 137–164, 1926.
353a. Troll, C., Büsserschnee in den Hochgebirgen der Erde. * Peterm. Geogr. Mitt. Ergänz. H. 240, 1942.
354. Wild, H., Ü. d. Differenzen d. Bodentemp. mit u. ohne Schneedecke nach d. Beob. im Konst. Observ. in Pawlowsk. * Mem. Petersburg. Akad. VIII. Ser. *5*, Nr. 8, 1897.

Chapter 17. The Air Layer above a Sod Cover.

355. Bartels, J., Verdunstung, Bodenfeucht. u. Sickerwasser. * Z. f. F. u. Jadgw. *65*, 204–219, 1933.
356. Berg, H. & Metzler, H. K., D. Temp. u. Feuchtefeld in 1.5 m Höhe über d. Flugplatz Hannover. * Erf. Ber. d. Deutsch. Flugwetterd. 9. Folge, Nr. 2, 1934.
357. Friedrich, W., Mess. d. Verdunstung vom Erdboden. * Deutsche Forschung *21*, 40–61, 1934.
358. Geiger, R., Mikroklimat. Beschreibung d. Wärmeschichtung am Boden. I. * Met. Z. *53*, 357–360, 1936.

359. —, — II. * Met. Z. *54*, 133–138, 1937.
360. —, — III. * Met. Z. *54*, 278–284, 1937.
361. Knochenhauer, W., Mikroklimat. Ergänz. zu: Inwieweit sind d. Temp. u. Feuchtigk.mess. unserer Flughäfen repräsentativ? * Erf. Ber. d. Deutsch. Flugwetterd. 9. Folge, Nr. 2, 1934.
362. Leick, E. & Propp, G., Bodentemp. u. Pflanzenwuchs in ihren wechselseit. Bez. auf d. Insel Hiddensee. * Mitt. a. d. Naturw. Ver. f. Neuvorpommern u. Rügen *57/58*, 79–113, 1930/31.
363. Münch, E., Nochmals Hitzeschäden an Waldpflanzen. * Naturw. Z. f. Land.- u. Forstw. *12*, 169–188, 1914.
364. —, Beob. ü. Erhitzung d. Bodenoberfläche. * Ibid. *13*, 249–260, 1915.
365. Newnham, E. V., Observ. of temp. close to the ground on clear calm nights. * Met. Mag. *65*, 59, 1930.
365a. Réthly, A., Istambul-Erenköi hömérsékleti megfigyeléseiböl (Deutsche Zus.fassung). * Az Idöyárás 1930, Nov./Dez.-Heft.
366. Rouschal, E., D. kühlende Wirkung d. Transpirationsstroms in Bäumen. * Ber. d. D. Botan. Ges. *57*, 53–66, 1939.
367. Runge, H., Entstehung v. Bodennebel durch Auspuffgase. * Z. f. angew. Met. *54*, 307–308, 1937.
368. Schwalbe, G., Ü. d. Temp.minima in 5 cm über d. Erdboden. * Met. Z. *39*, 41–46, 1922.

SUPPLEMENT TO PART I. HEAT TRANSFERS.

369. Albrecht, F., D. kalorimetr. Strahl-unters. u. d. met. Beob. in Lappland im Juni u. Juli 1927. * Abh. Pr. Met. I. *10*, Nr. 4, 1934.
370. —, Ü. d. Zusammenhang zw. tägl. Temp.gang u. Strahl.haushalt. * Gerl. B. *25*, 1–35, 1930.
371. —, E. Messgerät f. d. Mess. d. Wärmeumsatzes im Erdboden. * Met. Z. *49*, 294–299, 1932.
372. —, E. Strahlungsbilanzmesser z. Mess. d. Strahl.haushaltes v. Oberflächen. * Met. Z. *50*, 62–65, 1933.
373. —, D. Messgaräte d. Wärmeumatzes d. pflanzenbestandenen Erdoberfl. unter bes. Berücks. v. Mess. im Walde. * Z. f. angew. Met. *54*, 105–115, 137–146, 1937.
374. —, Messgeräte d. Wärmehaushaltes an d. Erdoberfl. als Mittel d. bioklimat. Forschung. * Met. Z. *54*, 471–475, 1937.
374a. —, Untersuchungen über den Wärmehaushalt der Erdoberfläche in verschiedenen Klimagebieten. * R. f. w., Wiss. Abh. *8*, Nr. 2, 1940.
374b. —, Der gegenwärtige Stand und die Aufgaben der Wärmehaushaltforschung. * Met. Z. *60*, 43–56, 1943.
374c. —, Untersuchungen am Strahlungsumsatzmesser mit Quecksilberthermometern. * Z. f. Met. *1*, 41–46, 1946.
375. v. Bezold, W., D. Wärmeaustausch an d. Erdoberfl. u. in der Atm. * Sitz-Ber. Berlin. Akad. 1892, S. 1139–1178.

376. Falckenberg, G., D. nächt. Wärmehaushalt bodennaher Luftschichten. * Met. Z. *49*, 369–371, 1932.
377. Franssila, M., Mikroklimat. Unters. d. Wärmehaushalts. * Helsinki 1936.
378. Homén, Th., D. tägl. Wärmeumsatz im Boden u. d. Wärmestrahl. zw. Himmel u. Erde. * Leipzig 1897.
379. Krügler, F., Nächtl. Wärmehaushaltsmess. an d. Oberfl. e. grasbewachsenen Ebene. * R. f. W. Wiss. Abh. *3*, Nr. 10, 1937.
380. Niederdorfer, E., Mess. d. Wärmeumsatzes über schneebedecktem Boden. * Met. Z. *50*, 201–208, 1933.
381. Okada, T., Ü. d. tägl. Wärmeaustausch in e. Schneedecke. * J. Met. Soc. Japan 1907, Nr. 4.
382. Sauberer, F., Mess. d. nächt. Strahl.haushalts d. Erdoberfläche. * Met. Z. *53*, 296–302, 1936.
383. —, Mess. d. Strahl.haushalts horizont. Oberfl. bei heiterem Wetter. * Met. Z. *54*, 273–278, 1937.
384. —, — — — bei Bewölkung 4–10. * Met. Z. *54*, 273–278, 1937.
385. —, Einiges ü. Erfahr. mit d. Strahl.bilanzmeser nach F. Albrecht. * Met. Z. *54*, 329–333, 1937.
386. Schmidt, Wilh., D. Wärmeumsätze an d. Erdoberfl. mit bes. Rücksicht a. d. Nachtfröste. * Fortschr. d. Landwirtsch. *3*, 385–396, 1928.
387. Schubert, J., D. Wärmeaustausch im festen Erdboden, in Gewässern u. in d. Atm. * Berlin 1904.

Bibliography for Part II

Chapters 18–20. Cold-Air Floods and Cold-Air Dams. Nocturnal Temperature Relationships in Valleys. Cold-Air Winds Down-Slope, Down-Valley and Glacier Winds.

388. Cornford, C. E., Katabatic winds and the prevention of frost damage. * Quart. J. *64*, 553–587, 1938.
389. Cox, H. J., Thermal belts and fruit growing in North Carolina. * M. W. Rev., Suppl. Nr. 19, 1923.
390. Defant, A., D. Abfluss schwerer Luftmassen auf geneigtem Boden. * Sitz-B. Berlin. Akad. 1933, S. 624–635.
391. Dobson, G. M. B., Frost hollows and fruit trees. * Quart. J. *64*, 588–591, 1938.
392. Ekhart, E., Neuere Unters. z. Aerologie d. Talwinde: D. period. Tageswinde in e. Quertale d. Alpen. * Beitr. Phys. d. fr. Atm. *21*, 245–268, 1934.
393. Fenner, G., D. belgische "Nebelkatastrophe" vom 3. u. 4. Nov. 1930. * Medizin. Welt 1935, S. 1860.
394. Flury, F., D. Todesursache bei d. Nebelkatastrophe im Maastal. * Arch. f. Gewerbepatholog. 7, 117–125, 1936.
394a. Guminski, R. D. lokale Klima d. Dniestertalabhangs bei Szutromince. * Bull. Mét. et Hydr. *15*, Nr. 10–12, 1935.

395. Hallenbeck, C., Night-temp. studies in the Roswell fruit district. * M. W. Rev. *46*, 364–373, 1918.
396. Henry, A. J., Cox on thermal belts and fruit growing in North Carolina. * M. W. Rev. *51*, 199–207, 1923.
397. Heywood, G. S. P., Katabatic winds in a valley. * Quart. J. *59*, 47–57, 1933.
398. Hoffrogge, Ch., Experim. Unters. d. bodennahen Luftströmungen am Hang u. im ebenen Gelände. * Z. f. Geophysik *15*, 184–213, 1939.
398a. Hough, A. F., Frost pocket and other microclimates in forests of the northern Allegheny Plateau. * Ecology *26*, 235–250, 1945.
399. Jaumotte, J., Sur le brouillard meurtrier de la vallée de la Meuse. * Ciel et Terre *47*, 100–106, 1931.
400. Koch, H. G., Die Saaletalnebel bei Jena. * Met. Z. *52*, 10–15, 1935.
400a. —, Über den Temperaturverlauf bei Saaletalnebel. * Z. f. Met. *1*, 122–128, 1947.
401. van Leeuwen, St., D. Nebelkatastrophe im Industriegebiet südl. v. Lüttich. * Münchn. Med. Wochenschr. 1931, S. 49.
402. Luft, R., D. Klima v. Bonn-Beuel. * B. f. angew. Met. *55*, 155–158, 191–197, 234–239, 1938.
403. Malsch, W., E. seltener Fall v. Vereisung. * Z. f. angew. Met. *55*, 31–32, 1938.
404. Manig, M., Nachweis d. Kaltluft d. erfrorene Dahlien. * Biokl. B. *6*, 22–23, 1939.
405. Marvin, C. F., Air drainage explained. * M. W. Rev. *42*, 583–585, 1914.
406. McDonald, W. F., Night radiation and unusual minim. temp. near New Orleans. * M. W. Rev. *68*, 181–185, 1940.
406a. Nägler, W., Thermische Eigentümlichkeit an Talstationen. * Z. f. angew. Met. *60*, 374–375, 1943.
407. Nitze, F. W., Unters. d. nächtl. Zirkulationsströmung am Berghang d. stereophotogramm. vermess. Ballonbahnen. * Biokl. B. *3*, 125–127, 1936.
408. Obrutschew, S., D. neue Kältepol in d. Jakut. Republ. * Met. Z. *48*, 359–360, 1931.
409. Pierce, L. T., Temp. variations along a forested slope in the Bent Creek Exper. Forest. * M. W. Rev. *62*, 8–12, 1934.
410. Predescou, C., Contrib. a l'étude des climats locaux a Cluj. * Min. de l'Agricult. et des Domaines Nr. 176, Bucarest 1929.
411. Reiher, M., Nächtl. Kaltluftfluss an Hindernissen. * Biokl. B. *3*, 152–163, 1936.
412. Scaëtta, H., Le climate écolog. de la dorsale Congo-Nil. * Inst. R. Col. Belge, Mém. Coll. in 4°. Bd. *3*, Brüssel 1934.
413. —, Les avalanches d'air (Luftlawinen) dans les Alpes et dans les hautes montagnes de l'Afrique centrale. * Ciel et Terre *51*, 79–80, 1935.

414. Schmauss, A., Luftlawinen in Alpentälern. * D. Met. Jahrb. f. Bayern 1926, Anhang F.
415. Schmidt, Wilh., D. tiefsten Min.temp. in Mitteleuropa. * Naturw. *18*, 367–369, 1930.
416. Schultz, H., Ü. Klimaeigentümlichk. im unt. Rheingau, unter bes. Berücks. d. Wisperwindes. * Frankf. Geogr. Hefte 7, Heft. 1, 1933.
417. Schulz, L., Lokalklimat. Unters. im Oberharz. * Biokl. B. *3*, 25–29, 1936.
418. Smolik, L., Beitr. z. Entstehung d. Kaltluftseen in d. Tälern. * Sbornik csl. Akad. zemed. Prag *11*, 200–204, 1936.
419. Tollner, H., Gletscherwinde in d. Ostalpen. * Met. Z. *48*, 414–421, 1931.
420. Wagner, A., Theorie u. Beob. d. periodischen Gebirgswinde. * Gerl. B. *52*, 408–449, 1948. Includes extensive bibliography.
421. Witterstein, F., Kleinklimat. Unters. im Rheingau. * Jahrb. d. Nass. Cer. f. Naturk. *83*, 59–105, 1936.
422. Young, F. D., Effect of topography on the temp. distrib. in southern California. * M. W. Rev. *48*, 462–463, 1920.
423. —, Nocturnal temp. inversions in Oregon and Calif. * M. W. Rev. *49*, 138–148, 1921.

Chapter 21. The Sunniness of Different Slopes.

423a. Albrecht, F., Ergebnisse von Dr. Haudes Beobachtungen usw. Rep. Scient. Exped. to the NW Prov. China under the leadersh. Dr. Sv. Hedin IX. * Met. 2. Stockholm 1941.
424. Bühler, A., Einfluss d. Exposition u. d. Neigung gegen d. Horiz. auf d. Temp. d. Bodens. * Mitt. d. Schweiz. Centr. Anst. f. d. forstl. Vers.Wesen *4*, 257–314, 1895.
424a. Eser, C., Berechn. d. Bestrahl.intensität gegen d. Horiz. verschieden geneigter Flächen. * Forsch. a. d. Geb. d. Agrik.physik. 7, 100–121, 1884.
425. Fritsch, E., Beitr. z. Erklärung d. Wanderungen d. Max. d. Bodentemp. * Met. Z. *6*, 151–153, 1871.
426. Gessler, R., D. Stärke d. unmittelb. Sonnenbestrahl. d. Erde in ihrer Abhängigk. v. d. Auslage unter verschied. Breiten u. zu versch. Jahreszeiten. * Abh. Pr. Met. I, *8*, Nr. 1, 1925.
426a. Haude, W., Ergebnisse der allgemeinen meteorologischen Beobachtungen nach den Drachenaufstiegen an den beiden Standlagern bei Ikengüng und am Edsen-gol 1931/32. * Rep. Scient. Exped. to the NW Prov. China under the leadersh. Dr. Sv. Hedin IX. Met. 1. Stockholm 1940.
426b. Kaempfert, W., Sonnenstrahlung auf Ebene, Wand und Hang. * Wiss. Abh. R. f. W. *9*, Nr. 3, 1942.
426c. —, Zur Besonnung südseitiger Spaliermauern. * Gartenbauwis. *17*, 531–542, 1943.

427. Kerner, A., Ü. Wanderungen d. Max. d. Bodentemp. * Met. Z. *6*, 65–71, 1871.
428. —, D. Änderung d. Bodentemp. mit d. Exposition. * Sitz-B. Wien. Akad. *100*, 704–729, 1891.
429. v. Kienle, J., D. tatsächl. u. d. astronom. mögl. Sonnenscheindauer auf verschieden expon. Flächen. * D. Met. Jahrb. f. Baden 1933, Anhang.
430. Kimball, H. H. & Hand, I. F., Daylight illumination on horizontal, vertical, and sloping surfaces. * M. W. Rev. *50*, 615–628, 1922.
431. Perl, G., D. Komponenten d. Intensität d. Sonnenstrahl. in verschied. geograph. Breiten. * Met. Z. *53*, 467–472, 1936.
432. Pers, M. R., Calcul du flux d'insolation sur une façade en pente. * La Mét. *11*, 429–435, 1935.
433. Schmidt, Wilh., Auswertung d. Wiener Sonnenstrahl.mess. f. prakt. Zwecke. * Fortschr. d. Landwirtsch. *1*, Heft 19, 1926.
434. Schoy, C., Probleme d. Besonnungsdauer. * Tät-B. Pr. Met. I. 1915, (21)–(44).
434a. Schütte, K., Die Berechnung der Sonnenhöhen für beliebig geneigte Ebenen. * Ann. d. Hydr. *71*, 325–328, 1943.
435. Wollny, E., Unters. ü. d. Einfluss d. Exposition auf d. Erwärm. d. Bodens. * Forsch. a. d. Geb. d. Agrik.physik *1*, 263–294, 1878.
436. —, Unters. ü. d. Einfl. d. Expos. d. Bodens auf dessen Feucht.-verhältnisse. * Ibid. *6*, 377–388, 1883.
437. —, Unters. ü. d. Feucht.- u. Temp.verhältn. d. Bodens bei verschied. Neigung des Terrains gegen d. Horizont. * Ibid. *9*, 1–70, 1886.
438. —, Unters. ü. d. Feucht.- u. Temp-verhältn. d. Bodens bei verschied. Neigung d. Terrains gegen d. Himmelsrichtung u. gegen d. Horizont. * Ibid. *10*, 1–54, 1888.

Chapter 22. Microclimatic Effect of Different Exposures to Sunshine.

439. Filzer, P., D. Mikroklima v. Bestandsrändern u. Baumkronen u. s. physiolog. Rückwirkungen. * Jahrb. f. wiss. Bot. *86*, 228–314, 1938.
440. Gerlach, E., Unters. ü. d. Wärmeverhältn. d. Bäume. * Diss. Leipzig 1929.
441. Härtel, O., Mikroklima u. Wachstum in Tulpenbeeten. * Biokl. B. *6*, 134–137, 1939.
442. Huber, Br., Aster linosyris, ein neuer Typus der Kompasspflanzen (Gnomonpflanzen). * Flora 29, 113–119, 1934.
443. —, Notiz ü. Kompasskrümmungen bei Agaven-Blütenständen. * Ber. D. Bot. G. *57*, 182–184, 1939.
443a. Kaempfert, W., Einfluss der Pflanzrichtung,- weite und -höhe auf die Besonnungszeit und -dauer. * Biokl. Beibl. *10*, 148–153, 1943.
444. Krenn, K., D. Bestrahlungsverhältn. stehender u. liegender Stämme. * Wien. Allg. F. u. Jagdztg. *51*, 50–51, 53–54, 1933.

445. Scamoni, A., Ü. Eintritt u. Verlauf d. männlichen Kiefernblüte. * Z. f. F. u. Jagdw. *70*, 289–315, 1938.
446. Schade, A., Ü. d. mittl. jährl. Wärmegenuss v. Webera nutans u. Leptoscyphus Taylori im Elbsandsteingebirge. * Ber. D. Bot. G. *35*, 490–505, 1917.
447. Schanderl, H., D. derzeitige Stand d. Kompasspflanzenproblems. * Biokl. B. *4*, 49–54, 1937. Includes wide bibliography.
448. Seeholzer, M., Rindenschäle u. Rindenriss an Rotbuche im Winter 1928/29. * Forstw. C. *57*, 237–246, 1935.

CHAPTERS 23 AND 24. THE SKIN OF AIR ON MOUNTAIN SLOPES, AND MORE ON THE INFLUENCE OF TOPOGRAPHY.

449. Brocks, K., Lokale Unterschiede u. zeitl. Änderungen d. Dichteschichtung in d. Gebirgsatm. * Met. Z. *57*, 62–73, 1940.
450. Büdel, A., D. Zugspitzbahnversuche. Teil I: D. Met. Jahrb. f. Bayern 1929, Anhang E; Teil II: ditto 1930; Teil III: ditto 1931.
451. Bujorean, G., Zwei extreme Standorte bei Cluj. * Veröff. d. Geobotam. Inst. Rübel *10*, 145–151, 1933.
452. Burckhardt, H. u. Flohn, H., D. atmosph. Kondensationskerne. * Abh. a. d. Geb. d. Bäder- u. Klimaheilkunde *3*, Berlin 1939.
452a. Ekhart, E., Neuere Untersuchungen der Aerologie der Talwinde: Die periodischen Tageswinde in einem Quertal der Alpen. * Beitr. z. Physik d. fr. Atm. *21*, 245–268, 1934.
453. Firbas, F., Vegetationsstudien auf d. Donnersberg im Böhm. Mittelgebirge. * Lotos (Prag) *76*, 113–172, 1928.
454. Geiger, R., Mess. d. Expositionsklimas (9 Teile). * Forstw. C. *49*, 665–675, 853–859, 914–923, 1927; *50*, 73–85, 437–448, 633–644, 1928; *51*, 37–51, 305–315, 637–656, 1929.
455. Geiger, R., Woelfle, M. & Seip, L. Ph., Höhenlage u. Spätfrostgefährdung (7 Teile). * Forstw. C. *55*, 579–592, 737–746, 1933; *56*, 141–151, 221–230, 253–260, 357–364, 465–484, 1934.
455a. Held, J. R., Temperatur u. relative Feuchtigkeit auf Sonnen- u. Schattenseite in einem Alpenlängstal. * Met. Z. *58*, 398–404, 1941.
456. Huttenlocher, F., Sonnen- u. Schattenlage. * Erdgesch. u. landeskundl. Abh. a. Schwaben u. Franken *7*, 1923.
457. Innerebner, F., Ü. d. Einfluss d. Exposition auf d. Temp.-verhältn. im Gebirge. * Met. Z. *50*, 337–346, 1933.
457a. Jelinek, A., Messung der Abkühlungsgrösse in einem Alpental. * Biokl, B. *9*, 145–150, 1942.
458. v. Kerner, F., Kleinklimatisches aus d. tirol. Gschnitztale. * Biokl. B. *3*, 54–55, 1936.
459. Kinzl, H. & Wagner, A., Pilotaufstiege in d. peruanisch. Anden. * Gerl. B. *54*, 29–55, 1938.
459a. Kreutz, W., & Wehrheim, H., Kleinklimaforschungen im Glocknergebiet in Anlehnüng an praktische Bedürfnisse. * Biokl, B. *9*, 23–34, 1942.

460. Künkele, Th., Spätfrost u. Höhenlage. * Forstw. C. *55*, 577–579, 1933.
461. Künkele, Th. & Geiger, R., Hangrichtung (Exposition) u. Pflanzenklima. * Forstw. C. *47*, 597–606, 1925.
462. Lauscher-Wittmann, A., Temp.verhältn. am Ostabhang d. Wienerwaldberge. * Biokl. B. *4*, 170–174, 1937.
463. Lautenbach, F., Expositionsklima oder Boden? * Allg. F. u. Jagdztg. *105*, 216–228, 1929.
464. Potzger, J. A., Microclimate and a notable case of its influence on a ridge in Central Indiana. * Ecology *20*, 29–37, 1939.
465. Reidat, R., Ü. unperiod. Anomalien d. tägl. Gangs d. Lufttemp. zu Erfurt u. auf d. Inselberge. * Mitt. d. Thüring. Landeswetterwarte, Heft 1, Weimar 1930.
465a. Schmauss, A., Absinken einer Inversion. * Z. f. angew. Met. *59*, 260–263, 1942.
466. Schmidt, Wilh., Einige Ergebnisse v. Temp.beob. an e. Hang. * Z. f. angew. Met. *47*, 204–211, 1930.
467. —, Hochgebirgsklima u. Technik. * Naturw. *22*, 381–384, 1934.
468. Sonntag, K., Klimaforschung im Weinbaugebiet. * Pfälz. Museum *48*, Heft 1/2, 1931.
469. —, D. Klima d. Kalmit. * Nicht veröff. Ber. ü. d. Kalmit-Observ.
470. Trankevitch, N. N., Some every-hour observ. on hygrometric air conditions, made in the points of a relief. * Rec. of the Far East Geophys. Inst. II (IX), 240–249, 1932.
471. Wagner, A., Ü. d. Feinstruktur d. Temp.gradienten an Berghängen. * Z. f. Geophysik *6*, 310–318, 1930.
472. Woeikof, A., Temp. u. Feucht. in Berg u. Tal im Amurland. * Met. Z. *31*, 140–143, 1914.

Chapter 25. Concerning the Range of Validity of Meteorological Stations.

473. v. Bascó, F. & Zólyomi, B., Kleinklima u. Vegetation auf d. Hochebene d. Bükkgebirges. * Biokl. B. *2*, 74–78, 1935.
474. Brooks, Ch. F., Einige Probl. kleinklimat. Unters. aus Neu-England. * Met. Z. *48*, 493, 1931.
475. —, An early morning weather profile from Cape Cod to central Massachusetts. * Bull. Americ. Met. Soc. *16*, 93–94, 1935.
475a. Burchard-Dostal, E., Über Differential-Klimogramme. * Biokl. B. *8*, 102–109, 1941.
476. Diesner, P., D. Geltungsbereich klimat. Stationen. * Wetter *43*, 21–24, 1926.
477. —, Weitere Bem. ü. d. Geltungsbereich klimat. Stat. * Wetter *44*, 93–95, 1927.
478. Dostal, E., Wie Temp. u. Feuchteverlauf sich innerh. v. 24 Stunden an benachbarten, aber versch. angelegten Stat. entwickelt. * Z. f. angew. Met. *57*, 178–182, 1940.

479. Geiger, R., Zum Geltungsbereich met. Stat. * Wetter *43*, 134–135, 1926.
480. Hartmann, W., Temp.mess. längs d. Arlbergbahn. * Z. f. angew. Met. *50*, 286–289, 1933.
481. Hettner, A., D. Wege d. Klimaforschung. * Geogr. Z. *30*, 117–120, 1924.
481a. Kaempfert, W., Bestimmungen der möglichen Sonnenscheindauer mit Hilfe eines einfachen Höhensuchers und der Tagbogenverkürzung. * RfW. Wiss. Abh. *9* Nr. 1, 1941.
482. Kassner, C., Ü. d. Einfluss d. Zahl d. Messstellen auf d. Darst. d. Niederschl.verteilung in Karten. * Tät-B. Pr. Met. I. 1916, (19)–(24).
483. Kern, H., D. Untersch. d. Extremtemp. zweier benachbarter Klimastat. * Z. f. angew. Met. *55*, 283–288, 1938.
484. Knoch, K., D. Einfluss geringer Geländeversch. auf d. met. Elemente im norddeutsch. Flachlande. * Abh. Pr. Met. I. *4*, Nr. 3. 1911.
485. —, Z. Methodik klimatolog. Forschung. * Tät-B. Pr. Met. I. 1924, 49–59.
486. Lauscher, F., Weitere Stud. ü. d. Sonnenstrahl-intens. in d. steir.-niederösterr. Kalkalpen. * Met. Z. *51*, 336–341, 1934.
487. —, Grundlagen d. Strahl.klimas d. Lunzer Kleinkl.stationen. * Beih. z. Jahrb. d. Zentralanst. f. Met. Wien Jahrg. 1931, Wien 1937.
488. Lauscher, F., Steinhauser, F. & Toperczer, M., E. Profil d. Sonnenstrahl.intens. durch d. steir.-niederösterr. Kalkalpen. * Met. Z. *49*, 300–306, 1932.
488a. Lautensach, H., Klimakunde als Zweig länderkundl. Forsch. * Geogr. Z. *46*, 393–408, 1940.
489. Ludwig, G., Gleichzeit. Mess. v. Kondensat.kernen an zwei benachb. Orten. * Met. Z. *53*, 106–108, 1936.
490. Schmauss, A., Zwei zeitgemässe Fragen. * Met. Z. *34*, 380–381, 1917.
491. Schmidt, Wilh., Biokl. Unters. im Lunzer Gebiet. * Naturw. *17*, 176–179, 1929.
492. —, Kleinklimat. Beob. in Österreich. * Geogr. Jahresber, aus Österr. *16*, 42–72, 1933.
493. —, D. Tagbogenmesser, e. Gerät z. Verfolgen d. Bahn d. Sonne am Himmel. * Met. Z. *50*, 328–331, 1933.
494. —, Observ. on local climatology in Austrian mountains. * Quart. J. *60*, 345–352, 1934.
495. —, Ü. neuere Messungs- u. Berechn.methoden d. Strahl.genusses f. bioklimat. Zwecke. * Strahlentherapie *61*, 689–696, 1938.
496. Schmidt, Wilh. & Schwabl, W., Strahl.genuss u. Ertrag im Gebirgsland. * Biokl. B. *2*, 78–83, 1935.
497. Schulz, L., D. Einfluss d. Harzes auf Wetter u. Witterung im Frühjahr 1936. * R. f. W. Wiss. Abh. *6*, Nr. 1, 1939.

498. Stepanowa, N., D. Genauigk. d. Beob. u. d. Mikrostruktur des Elementes im Raum. * Met. i Hydrol. Moskau 1936, Nr. 8.
499. Tinn, A. B., Local temp. variations in the Nottingham district. * Quart. J. *64*, 391–401, 1938.
500. Topolansky, M., D. Geltungsbereich klimatolog. Stationen. * Wetter *41*, 125–128, 1924.

SUPPLEMENT: THE MICROCLIMATE OF CAVES.

501. Buxton, P. A., Climate in caves and similar places in Palestine. * J. of Animal Ecology *1*, 152–159, 1932.
501a. —, The climate in which the rat-flea lives. * Ind. Journ. Med. Res. *20*, 281–297, 1932.
502. Fugger, Beob. in d. Eishöhlen d. Untersberges bei Salzburg. * Mitt. Ges. f. Salzburger Landesk. *28*, 1888.
503. Hauser, E. & Oedl, R., Eishöhlen. E. Beitrag zu ihrer physikal.-met. Erklärung. * Naturw. *9*, 721–725, 1921.
503x. Hess, H., Leo Handl's Temperatur-Messungen des Eises und der Luft in den Stollen des Marmolata-Gletschers und denen des Ortlergebietes 1917–1918. * Zeitschr. f. Gletscherkunde *27*, 168–171, 1940.
503y. Kreutz, W., & Wehrheim, H., Klimastudien diesseits und jenseits des Tauernkamms. * Z. f. angew. Met. *59*, 369–390, 1942.
503a. Lautensach, H., Unterirdischer Kaltluftstau in Korea. * Peterm. Geogr. Mitt. *85*, 353–355, 1939.
504. Mrose, H., E. seltsame Höhlenvereisung. * Z. f. angew. Met. *56*, 350–353, 1939.
505. Oedl, R., Ü. Höhlenmeteorologie, m. bes. Rücks. a. d. grosse Eishöhle im Tennengebirge. * Met. Z. *40*, 33–37, 1923.
506. Paulcke, W., Prakt. Schnee- u. Lawinenkunde (Verständl. Wiss. *38*). Berlin, J. Springer, 1938.
507. Penck, A., D. Temp.-verhältn. d. Grotten v. St. Canzian b. Triest. * Met. Z. *6*, 161–164, 1889.
508. Roschkott, A., Ü. Temp.verhältn. in Höhlen. * Met. Z. *38*, 33–38, 1921.
509. Steiner, L., D. Temp.-verhältn. d. Eishöhle v. Dobsina. * Met. Z. *39*, 193–199, 1922.

CHAPTER 26. THE HEAT ECONOMY OF PLANTS, AND PLANT TEMPERATURES.
(The bibliography is here only so far extended as is not already covered in the collected works of Bruno Huber (*514*)).

510. von Angerer, E., Landschaftsphotographien in ultrarotem u. ultraviolettem Licht. * Naturw. *18*, 361–364, 1930.
511. Egle, K., Z. Kenntnis d. Lichtfeldes u. d. Blattfarbstoffe. * Planta *26*, 546–583, 1937.
512. Filzer, P., Nordafrikan. Wüste u. süddeutsche Steppenheide, e. ökolog. Parallele. * Festschr. f. C. Uhlig, Öhringen 1932.

513. Graininger, J., The internal temp. of fruit tree buds II. * Ann. appl. Biolog. *36*, 1–13, 1939.
514. Huber, Br., D. Wärmehaushalt d. Pflanzen (Naturw. u. Landwirtsch., her. v. Boas *17*). * Freising-München, Datterer, 1935.
515. —, Mikroklimat. u. Pflanzentemp.registrierungen mit d. Multithermograph v. Hartm. & Braun. * Jahrb. f. wiss. Bot. *84*, 671–709, 1937.
515a. —, Physiologische Rhythmen in Baum. * Met. Rundschau *1*, 144–147, 1947.
516. Hummel, K., Ü. Temp. in d. Sojablüte. * Biokl. B. *6*, 13–17, 1939.
516a. —, Über Temperaturen in Winterknospen bei Frostwitterung. * Met. Rundschau *1*, 147–150, 1947.
517. Kessler, O. W. & Schanderl, H., Pflanzen under d. Einfluss verschied. Strahl.intensitäten. * Strahlentherapie *39*, 283–302, 1931.
518. Mäde, A., E. Beitrag z. Mikroklima e. Obstbaumes. * Gartenbauwiss. *12*, 127–137, 1938.
519. —, D. Einfadenwiderstandsthermometer als Messgerät z. Best. d. Oberfl.temp. v. Blättern. * Biokl. B. *6*, 11–13, 1939.
519a. —, Temperaturuntersuchungen an Obstbäumen. * Gerl. B. *59*, 201–213, 1942.
520. Michaelis, G. & P., Ökolog. Stud. an d. alpinen Baumgrenze III: Ü. d. winterl. Temp. d. pflanzl. Organe, insbes. d. Fichte. * Beih. z. Botan. Centralbl. *52*, 333–377, 1934.
521. Orth, R., Strahlung, Lichtfeld u. Pflanze. * Biokl. B. *5*, 68–75, 1938.
521a. Schanderl, H., & Kaempfert, W., Über die Strahlungsdurchlässigkeit von Blättern und Blattgeweben. * Planta *18*, 700–750, 1933.
522. Sauberer, F., Z. Kenntnis d. Strahl.verhältn. in Pflanzenbeständen. * Biokl. B. *4*, 145–155, 1937.
523. Seybold, A., Ü. d. Lichtfaktor photophysiolog. Prozesse. * Jahrb. f. wiss. Bot. *82*, 741–795, 1936.
524. Smith, A. M., On the internal temp. of leaves in tropical insolation. * Ann. Royal Botan. Gard. Peradeniya *4*, 1909.
525. Ullrich, H. & Mäde, A., Stud. ü. d. Ursachen d. Frostresistenz. I. Unters. d. Temp.austauschs an Rizinusblättern durch Mess. d. Oberfl.temp. * Planta *28*, 344–351, 1938.
526. — —, II. Unters. ü. d. Temp.verlauf b. Gefrieren v. Blättern u. Vergleichsobjekten. * Planta *31*, 251–262, 1940.
526a. Wegener, K., Die Meteorologie im Leben der Pflanze. * Z. f. angew. Met. *59*, 321–338, 1942.
527. Weger, N., Über Tütentemperaturen. * Biokl. B. *5*, 16–19, 1938.
527a. Weger, N., Herbst, W. & Rudloff, C. F., Witterung u. Phän. d. Blühphase d. Birnbaums. * R. f. W. Wiss. Abh. *7*, Nr. 1, 1940.
528. Young, F. D., Substitution of fruit temp. for air temp. in regulating orchard heating for oranges. * M. W. Rev. *52*, 381–387, 1924.

Chapter 27. Radiation and Temperature Relationships in a Low Plant Cover.

529. Filzer, P., Unters. ü. d. Mikroklima in niederwüchsigen Pflanzengesellsch. * Beih. z. Botan. Centralbl. *55*, 301–346, 1936.
530. Fleischmann, R., Temp.mess. in reifenden Getreidefeldern u. and. Kulturen. * Fortschr. d. Landwirtsch. *3*, 1928.
531. —, Beitr. z. Kenntnis d. Mikrokl. in Getreidefeldern vor Ausbruch d. Rostes. * Az Idöjárás *34*, VII/VIII, 1930.
532. Geiger, R., Unters. ü. d. Pflanzenklima. * Mitt. d. Staatsforstverwaltung Bayerns *17*, 1926.
533. Kanitscheider, R., Temp.mess. in e. Bestande v. Legföhren. * Biokl. B. *4*, 22–25, 1937.
534. Kirchner, R., Beob. ü. d. Mikroklima d. Weinberge. * Mitt. d. Pfälz. Ver. f. Naturkunde u. Naturschutz *5*, 1936.
535. Kleĉka, A., Mikroklimat. Beob. in Wiesenbeständen. * Sbornik csl. Akad. zemed Prag *11*, 2–10, 1936.
536. Kreutz, W., Agrarmet. Stud. ü. Bestandsklima, ü. Windschutz u. ü. Transpirat.verhältn. im Gewächshaus. * R. f. W. Wiss. Abh. *2*, Nr. 7, 1937.
537. Lundegardh, H., Klima u. Boden in ihrer Wirkung auf d. Pflanzenleben. * Jena 1930.
538. Mäde, A., Widerstandselektr. Temp.mess. in e. Topinamburbestand. * R. f. W. Wiss. Abh. 2, Nr. 6, 1936.
539. —, Ü. d. Temp.verlauf in Beständen. * Gartenbauwiss. *15*, 312–333, 1940.
539a. —, Die Agrarmeteorologie in der Pflanzenzüchtung. * R. f. W. Wiss. Abh. *9*, Nr. 6, 1942.
540. Putod, R., Action de l'enherbement sur les reboisements en Algérie. * Rev. des Eaux et Forêts 75, 412–426, 1937.
541. Ramdas, L. A., Kalamkar, R. J. & Gadre, K. M., Agricultural Stud. in Microclimatology I. * Indian J. of Agric. Sc. *4*, 451–467, 1934.
542. — — —, Ditto II. * Ibid. 5, 1–11, 1935.
543. Scaëtta, H., Bioclimats; climats des associations et microcl. de haute montagne en Afrique Central Equatoriale. * Journ. d'agron. colon. Juni 1933 (Belgien).
543a. Schmauss, A., D. Klimaraum der Jungpflanze. * Mitt. d. Herm. Göring-Akad. d. D. Forstwiss. *1*, 173–180, 1941.
544. Sonntag, K., Ber. ü. d. Arb. d. Kalmit-Observ. * D. Met. Jahrb. f. Bayern 1934, Anhang D.
545. Tamm, E., Vergl. Temp.mess. in d. Zone d. Pflanzenklimas. * Landw. Jahrb. *83*, 457–554, 1936.
546. —, — II. * Ditto *88*, 479–548, 1939.
547. —, — III. * Ditto *89*, 259–318, 1939.

548. Trankevitch, N. N., On the study of the phytoclimate of a wheat field. * Rec. Far East Geophys. Inst. Wladiwostok *1*, 271–283, 1931.
549. Troll, C. & Wien, K., Oldeani-Ngorongoro. * Wiss. Veröff. d. Mus. f. Länderk. z. Leipzig, N. F. *3*, 95–116, 1935.
550. Wegener, A., D. Wesen d. Baumgrenze. * Met. Z. *40*, 371–372, 1923.
551. Weger, N., Mikroklimat. Stud. in Weinbergen. * Biokl. B. *6*, 169–179, 1939.
552. Wild, H., Diff. d. Bodentemp. mit u. ohne Vegetat. oder Schneedecke. * Mem. Petersburger Akad. *8*, Ser. T, 1897.

Chapter 28. Humidity and Wind Relationships in a Low Plant Cover.

(Insofar as not already covered by Chapter 27.)

553. Büdel, A., Unters. d. Wärmeschutzwirkung v. Gittern u. Pflanzen. * R. f. W. Wiss. Abh. *4*, Nr. 1, 1938.
554. Durst, C. S., Notes on the variations in the structure of wind over different surfaces. * Quart. J. *59*, 361–371, 1933.
555. Filzer, P., Experiment. Beitr. z. Synökologie d. Pflanzen I. * Jahrb. f. Wiss. Bot. *79*, 9–130, 1933.
556. —, Unters. ü. d. Wasserumsatz künstl. Pflanzenbestände. * Planta *30*, 205–223, 1939.
557. Firbas, F., Stud. ü. d. Standortscharakter auf Sandstein u. Basalt. * Beih. z. Botan. Centralbl. *40*, 253–409, 1924.
558. Fleischmann, R., Windschäden in Maisfeldern. * Biokl. B. *3*, 123–125, 1936.
559. Kestermann, A., Abkühl.studien mit bes. Berücksicht. d. Frigorigraphen n. Büttner u. Pfleiderer. * Biokl. B. *7*, 1–16, 1940.
560. Kreutz, W., D. Windschutzproblem. * Biokl. B. *5*, 10–16, 1938.
561. Paeschke, W., Mikroklimat. Unters inerhalb u. dicht über verschiedenart. Bestand. * Biokl. B. *4*, 155–163, 1937.
562. Schmauss, A., Über Sturmgefährdungen. * Forstw. C. *42*, 189–194, 1920.
563. Stocker, O., Klimamess. auf kleinstem Raum an Wiesen-, Wald- u. Heidepflanzen. * Ber. D. Bot. G. *41*, 145–150, 1923.
564. —, D. Wasserhaushalt ägypt. Wüsten- u. Salzpflanzen. * Botan. Abh., Goebel, Heft 13, Jena 1928.
565. Wenger, R., D. wolkenfreie Raum an d. Erdoberfläche. * Met. Z. *32*, 20–22, 1915.

Certain References on Dew and Hoar Frost Questions as Microclimatic Problems.

566. Andrianoff, P., Tauregistrier-Aräometer. * Met. Z. *44*, 425–429, 1927.

567. Bernick, W., Unters. ü. d. Taufall auf d. Insel Hiddensee u. s. Bedeutung als Pfl.faktor. * Mitt. Naturwiss. Ver. f. Neuvorpommern u. Rügen *65/66*, 1938.
568. Fritzsche, G., Vergl. Mess. mit. Leickschen Tauplatten. * Biokl. B. *1*, 66–73, 1934.
569. Hiltner, E., D. Tau u. s. Bedeutung f. d. Pflanzenbau. * Wiss. Arch. f. Landwirtsch. *3*, 1–70, 1930.
570. —, D. Tau u. s. Bedeutung f. d. Wasserhaushalt d. Kulturpflanzen. * Prakt. Bl. f. Pfl.bau u. Pfl.schutz *8*, 223, 1931.
571. Keller, H., Ü. Taumessungen im ariden Hochland Transvaals. * Met. Z. *50*, 321–324, 1933.
572. Kessler, O., D. Tauschreiber Kessler-Fuess. * Biokl. B. *6*, 23–26, 1939.
573. Knoche, W., E. Bemerk. ü. d. Taufall. * Met. Z. *56*, 322, 1939.
573a. Kyriazopoulos, B., Drosographe: Instr. pour l'étude de la rosée, la gelée blanche et la pluie. * Comm. Met. Agricole, Tag. Ber. Salzburg 1937, S. 97–100, Leyden 1938.
573b. Lehmann, P., and Schanderl, H., Tau und Reif. * R.f.W. Wiss. Abh. *9*, Nr. 4, 1942.
574. Leick, E., Z. Methodik d. relat. Taumessung. * Beih. z. Botan. Centralbl. *49*, Erg.-B., 160–189, 1932.
575. —, D. Tau als Standortsfaktor. * Ber. D. Bot. G. *51*, 409–442, 1933.
576. Mrose, H., E. volumenometr. Taumessgerät. * Z. f. angew. Met. *56*, 137–149, 1939.
577. Rubenson, R., V. d. Temp. u. Feucht.verhältn. in d. untersten Luftschichten bei d. Bild. d. Taus. * Met. Z. *11*, 65–75, 1876.
578. Rudel, K., Natürl. Psychrometer. * Met. Z. *20*, 33–35, 1903.
579. Schubert, J., Ü. Niederschl.formen an d. Erdoberfl. * Z. f. F. u. Jagdw. *49*, 389–393, 1917.
580. Stephen, J., D. Tauproblem (Sammelreferat). * Biokl. B. *5*, 75–81, 1938.
580a. —, Zum Tauproblem. * Biologie generalis *17*, 204–229, 1943.
581. Stephen, J. & Mildebrath, E., Registr. Taumessung. * Biokl. B. *5*, 34–39, 1938.
582. Stüve, G., Z. Kenntnis d. Kristallisation d. Wasserdampfes aus d. Luft. * Gerl. B. *32*, 326–335, 1931.
583. Sutton, J. R., On some met. conditions controlling nocturnal radiation. * Transact. Roy. Soc. of South Africa *2*, Part 5, 1912.
584. Visser, S. W., E. neuer Tau-Registrierapparat. * Met. Z. *51*, 388–390, 1934.
585. Zattler, F., Agrarmet. Beitr. z. Tauproblem auf Grund v. Mess. im Hopfengarten. * Wiss. Arch. f. Landwirtsch. *8*, 371–404, 1932.

Chapter 29. Forest Meteorology, Forest Climatology and Stand Climate.

585a. Amelung, W., & Pfeiffer, C. A., Die Einwirkungen des Waldklimas auf den Menschen. * Klin. Wochenschr. *24/25*, 563–566, 1947.

586. Bates, C. G. & Henry, A. J., Forest and stream-flow experiment at Wagon Wheel Gap, Colo. * M. W. Rev., Suppl. *30*, 1928.

587. Blanford, H. F., On the influence of Indian forests on the rainfall. * J. Asiatic Soc. of Bengal 56, Part II, 1, 1887.

588. Brooks, C. E. P., The influence of forests on rainfall and runoff. * Quart. J. *54*, 1–13, 1928.

589. Burger, H., Waldklimafragen I: Met. Beob. i. Freien u. in e. Buchenbestand. * Mitt. Schweiz. Centr.Anst. f. d. forstl. Vers.w. *17*, 92–149, 1931.

590. —, — II: Met. Beob. i. Freien, in e. Buchen- u. e. Fichtenbestand. * Ibid. *18*, 1–54, 1933.

591. Deines, G. D. forstl. Standortslehre. * Mitt. a. Forstwirtsch. u. F. wiss. *9*, 387–352, 1938.

592. Ebermayer, E., D. physikal. Einwirkungen d. Waldes auf Luft u. Boden. * Aschaffenburg 1873.

593. —, Klimat. Wirk. d. Waldes auf s. Umgebung. * Met. Z. *10*, 201–214, 1893.

594. Engler, A., Unters. ü. d. Einfluss d. Waldes auf d. Stand d. Gewässer. * Bürich, Verlag Beer, 1919.

595. Eredia, F., Ricerche sull'influenza delle litoranee e del bosco mediterraneo sul clima. * Comm. Met. Agricole, Tag.-Ber. München 1932, S. 138–139, Utrecht 1933.

596. Ernst, F., D. Bedeut. d. Klimaextreme f. d. Waldbau in Mitteleuropa. * Forstw. C. *56*, 86–102, 1934.

597. Faust, R., D. Abkühlungsklima im Walde u. auf freiem Felde nach Frigorimeterregistr. * Veröff. Geoph. I. Leipzig *8*, Heft 1, 1936.

598. Geiger, R., Wald u. Klima. * Mitt. d. Reichsforstwirtschaftsrates Berlin 1932.

599. —, Ü. d. Wechselwirkung v. Wetter u. Wald. * Fostarchiv *15*, 195–200, 1939.

600. —, Wetter u. Klima als Standortsfaktor. * Neudammer Forstl. Lehrb., 10. Aufl. 1949.

600a. —, Wider die Gefährdung des Landes durch Waldzerstörung. * Allg. Forstz. *2*, 137–140, 1947.

600b. Gusinde, M., and Lauscher, F., Meteorologische Beobachtungen im Kongo-Urwald. * Sitz.-B. Wien Akad. *150*, 281–347, 1941.

601. Hall, R. C., Climatic diff. between forested and cut-over areas in New Hampshire etc. * Biokl. B. *6*, 185–186, 1939.

602. Hamberg, H. E., De l'influence des forêts sur le climat de la Suéde. 5 Teile. Stockholm 1885–96.

603. Hirata, T., Contrib. to the problem of the relation between the forest and water in Japan. * Imper. Forestry Exper. Stat. Meguro 1929.

604. Hoppe, E., Sind d. forstl.-met. Beob. in d. bisher. Weise fortzusetzen oder sollte eine Änderung d. bish. Systems eingeführt werden? * Ref. v. 2. Kongr. d. intern. Verb. forstl. Vers.A. 1896.

605. Ijjász, E., D. Geschichte, Organisation u. Forsch.richtung d. forstl. Met. Ungarn. * 9. Kongr. d. intern. Verb. forstl. Forsch.-Anst. 1936.

606. Kaminsky, A., Beitrag z. Frage ü. d. Einfluss d. Aufforstung d. Waldlichtungen in Indien auf d. Niederschl. * Nachr. d. Geophys. Central. I. Leningrad Nr. 4 (Year?).

606a. Kirwald, E., Bekämpfung des Bodenabtrags und Regelung des Wasserhaushalts in Gebirgen. * Forstwiss. C. u. Thar. Forstl. Jahrb. (Kriegsgemeinschaftsausgabe) 1944, 37–40.

607. Koloskoff, P. J., Air humidity in the forest and outside it. * Rec. Far East Geophys. Inst. Wladiwostock *1*, 255–270, 1931.

608. von Lorenz-Liburnau, Resultate forstl.-met. Beob. * Mitt. a. d. forstl. Vers.wesen Österr. *12* und *13*, Wien 1890.

609. Lossnitzer, H., Neuere Erkenntnisse in d. forstl. Met. * D. Deutsche Forstwirt *21*, 337–338, 1939.

610. Meyer, A. F., D. Wald in s. Wirkung auf d. Menge d. für d. Trinkwasserversorgung erschliessbaren Wassers. * D. Gas- u. Wasserfach *78*, 253–258, 273–277, 293–296, 312–318, 1935.

611. Müttrich, A., Ü. d. Einfluss d. Waldes auf d. period. Veränd. d. Lufttemp. * Z. f. F. u. Jagdw. *22*, 385–400, 449–458, 513–526, 1890.

612. —, Ü. d. Einfluss d. Waldes auf d. Grösse d. atmosph. Niederschläge. * Z. f. F. u. Jagdw. *24*, 27–42, 1892.

613. —, Ü. d. Einrichtung v. met. Stat. z. Erforsch. d. Einwirkung d. Waldes auf d. Klima. * Z. f. F. u. Jagdw. *32*, 297–304, 1900.

613a. Paffen, K. H., Waldverwüstung und Wasserhaushalt. * Erdkunde *1*, 209–212, 1947.

614. Rubner, K., D. pflanzengeogr.-ökolog. Grundlagen d. Waldbaus. 3. Aufl. Neudamm, Neumann, 1934.

614a. Sachsse, H. F., Walderhaltung und Aufforstungen in den Erzgebirgshochlagen. * Thar. Forstl. Jahrb. *93*, 374–395, 1942.

615. Schenck, C. A., Fremdländ. Wald- u. Parkbäume. Bd. 1: Klimasektionen u. Urwaldbilder. Berlin, P. Parey, 1939.

616. Schreiber, P., D. Einwirkung d. Waldes auf Klima u. Witterung. * Thar. Forstl. Jahrb. *49*, 85–204, 1899.

617. Schubert, J., D. jährl. Temp.extreme im Felde u. im Walde. * Z. f. F. u. Jagdw *25*, 28–36, 1893

618 —, Ü. d. Ermittl. d. Temp. u. Feucht.Unterschiede zw. Wald u. Feld. * Z. f. F. u. Jagdw. *25*, 441–456, 1893.

619. —, Temp. u. Feucht. d. Luft auf d. Felde u. im Kiefernwalde. * Z. f. F. u. Jagdw. *27*, 509–525, 1895.

620. —, D. jährl. Gang d. Luft- u. Bodentemp. im Freien u. in Waldungen. Berlin, J. Springer, 1900.
621. —, Vergl. Temp. u. Feucht.Bestimmungen. * Abh. Pr. Met. 1. *1*, Nr. 7, 1901.
622. —, D. Niederschlag in d. Annaburger Heide 1901 bis 1905. * Z. f. F. u. Jagdw. *40*, 622–633, 1908.
623. —, Temp. u. Feucht. zu Eberswalde im Freien u. in e. Buchenschonung. * Z. f. F. u. Jagdw. *45*, 764–775, 1913.
624. —, D. Höhe d. Schneedecke im Walde u. im Freien. * Z. f. F. u. Jagdw. *46*, 567–572, 1914.
625. —, D. Einwirkung d. grünen Buchenwaldes auf d. Temp. u. Feucht. d. Luft. * Wetter, Sonderheft f. Assmanns 70. Geb. 1915.
626. —, Stud. über See- u. Waldklima. * Z. f. Balneologie, Klimat. u. Kurorthyg. *10*, 6–11, 99–105, 112–115, 1917/18.
627. —, Niederschl., Verdunst., Bodenfeucht., Schneedecke in Waldbeständen u. i. Freien. * Met. Z. *34*, 145–153, 1917.
628. —, Ü. d. Windstärke in d. unteren Luftsch. u. d. Windschutz d. Waldes. * Silva 1922, S. 377–381.
629. —, Ü. d. Einfluss d. Waldes auf d. Niederschläge im Geb. d. Letzlinger Heide. * Z. f. F. u. Jagdw. *69*, 604–615, 1937.
630. Seltzer, P., Influence d'une forêt sur la temp. de l'air. * C. R. Paris *199*, II, 435–438, 1934.
631. Walter, A., Ü. d. Einfluss d. Waldes auf d. Regenfall in Mauritius. * Met. Z. *26*, 87–88, 1909.
632. —, Forest and climate. * Comm. Met. Agricole, Tag-Ber. Salzburg 1937, S. 63–64, Leyden 1938.
633. Weber, R., D. Bedeutung d. Waldes u. d. Aufgaben d. Forstwirtschaft (neu bearb. v. H. Weber). * Loreys Handb. d. Forstwiss. 4. Aufl., Band I, S. 43–187. Tübingen, H. Laupp, 1926.
634. Wlissidis, T., Ü. d. Einwirk. d. Waldes auf d. Klima. * C. f. d. ges. Forstwesen *44*, 94–99, 1918.
635. Woeikof, A., D. Klimate d. Erde (Kap. 12 u. 13). Jena 1887.
636. Woelfle, M., Waldbau u. Forstmeteorologie. 2 Aufl., Landw. Verlag Munchen 1950.

Chapter 30. Radiation Relationships in an Old Stand.

637. Ångström, A. & Wallén, C. Chr., On the illumination in stands of diff. character and density. * Comm. Met. Agricole, Tag.-Ber. Salzburg 1937, S. 81–82, 1938.
638. Bartels, J., D. Strahlung u. ihre Bedeut. f. d. Klima. * Z. f. F. u. Jagdw. *62*, 537–563, 1930.
639. Brocks, K., D. räuml. Verteilung d. Beleucht.stärke im Walde. * Z. f. F. u. Jagdw. *71*, 47–53, 1939.
640. Deinhofer, J. & Lauscher, F., Dämmerungshelligkeit (Beob. u. Überlegungen). * Met. Z. *56*, 153–159, 1939.

640a. Eidmann, H., Meine Forschungsreise nach Spanisch-Guinea. * D. Biologe *10*, 1–13, 1941.
641. Knuchel, H., Spektrophotometr. Unters. im Walde. * Mitt. Schweiz. Centr. Anst. f. d. forstl. Vers.w. *11*, 1–91, 1914.
642. Lauscher, F. & Schwabl, W., Unters. ü. d. Helligk. im Wald u. am Waldrand. * Biokl. B. 1, 60–65, 1934.
643. Mitscherlich, G., D. Forstamt Dietzhausen. * Z. f. F. u. Jagdw. *72*, 149–188, 1940.
643a. Nägeli, W., Lichtmessungen im Freiland und im geschlossenen Altholzbestand. * Mitt. Schweiz. Centr. Anst. f. d. forstl. Versuchswesen *21*, 250–306, 1940.
644. Sauberer, F. & Trapp, E., Helligk.mess. in e. Flaumeichenbuschwald. * Biokl. B. *4*, 28–32, 1937.
645. Schmidt, Wilh., D. Lichtgenuss unter e. Obstbaum; Mess. nach neuer Methode. * Fortschr. d. Landwirtsch. *8*, 29–33, 1933.
646. Trapp, E., Unters. ü. d. Verteilung d. Helligk. in e. Buchenbestand. * Biokl. B. 5, 153–158, 1938.
647. Wiesner, J., D. Lichtgenuss d. Pflanzen. Leipzig, W. Engelmann, 1907.
648. Zederbauer, E., D. Lichtbedürfnis d. Waldbäume u. d. Lichtmessmethoden. * C. f. d. ges. Forstwesen *33*, 325–330, 1907.

Chapters 31 and 32. Temperature and Humidity Relationships in an Old Stand. Wind and Precipitation in an Old Stand.

649. Geiger, R., Unters. ü. d. Bestandsklima (6 Teile). * Forstw. C. *47*, 629–644, 848–854, 1925; *48*, 337–349, 495–505, 523–532, 749–758, 1926.
649a. —, Die Witterungsbedingungen für Waldgrossbrände. * Mitt. Reichsinst. f. Forst. u. Holzwirtsch. Hamburg-Reinbek, Nr. 5, 1948.
650. Geiger, R. & Amann, H., Forstmet. Mess. in e. Eichenbestand (5 Teile). * Forstw. C. *53*, 237–250, 341–351, 705–714, 809–819, 1931; *54*, 371–383, 1932.
651. Hoppe, E., Regenmessungen unter Baumkronen. * Mitt. a. d. forstl. Vers.wesen Österr. *21*, Wien 1896.
652. von Obolensky, N., Effect of arborous vegetation on the temp. of the soil and the temp. and humidity of the air. * J. of Geophys. and Met. *3*, 113–139, Moskau 1926.
652a. Priehäusser, G., Bodenfrost, Bodenentwicklung u. Flachwurzeligkeit d. Fichte. * Forstw. C. *61*, 329–342, 381–389, 1939.
652b. Sauberer, F., & Trapp, E., Temperatur und Feuchtemessungen in Bergwäldern. * Centralbl. f. d. ges. Forstwesen *67*, 233–244, 257–276, 1941.
653. Seltzer, P., Sur la répartition verticale de la temp. en forêt. * Siehe Ref. in Biokl. B. 2, 55, 1935.

654. Ungeheuer, H., Mikroklima in e. Buchenhochwald am Hang. * Biokl. B. *1*, 75–88, 1934.

Chapters 33, 34 and 35. The Influence of the Make-up of the Stand on Its Climate.

The Microclimate of Circular Slashings, Clearings and Cuttings. The Climate of the Stand Border.

655. Ångström, A., Jordtemp. i. bestand av olika täthet. * Medd. Stat. Met. Hydr. Anst. Stockholm *29*, 187–218, 1936.
656. Becker, R., Unters. z. Struktur d. Luftströmung nach synopt. Methoden. * Deutsche Forschung *14*, 35–40, 1930.
657. Boos, Unters. ü. d. Bestandsinnenklima im Pr. Forstamt Erdmannshausen. * Mit. a. Forstwirtsch. u. F.wiss. *10*, 254–259, 1939.
658. Burger, H., Waldklimafragen III: Met. Beob. im Freien, in e. gleichaltrigen Fichtenbestand u. im Tannen-Fichten-Plenterwald b. Oppligen. * Mitt. Schweiz. Centr.Anst. f. d. forstl. Vers.w. *18*, 153–192, 1933.
659. Cour, P. la, Skovenes Indflydelse paa Varmen. * Ref.: Z. d. österr. Ges. f. Met. *7*, 254–256, 1872.
660. Danckelmann, B., Spätfrostbeschäd. im märk. Walde. * Z. f. F. u. Jagdw. *30*, 389–411, 1898.
661. Descombes, P., Les forêts, les pluies et les condensations occultes. * Annuaire Soc. Mét. de France *66*, 38–46, 1922/23.
662. Dieckmann, A., Vers. z. Niederschl.mess. aus treib. Nebel. * Met. Z. *48*, 400–402, 1931.
662a. Dienert, F., Contrib. à l'étude des condensations occultes. * C. R. Paris *198*, 1261–1263, 1934.
663. Dörffel, K., D. physik. Arbeitsweise d. Gallenkampschen Verdunst.mess. u. s. Anwendung auf mikrokl. Fragen. * Veröff. Geophys. I. Leipzig *6*, Heft 9, 1935.
663a. Eggler, J., Kleinklimatische Untersuchungen in den Flaumeichenbeständen bei Graz. * Biokl. B. *9*, 94–110, 1942.
664. Geiger, R., D. Windbewegung auf Waldschneisen. * Biokl. B. *1*, 134–137, 1934.
665. —, D. Beschattung am Bestandsrand. * Forstw. C. *57*, 789–794, 1935.
666. —, Weitere Bem. z. Klima am Bestandsrand. * Forstw. C. *58*, 262–266, 1936.
667. —, D. Standortsklima in Altholznähe. * Mitt. d. Herm. Göring-Akad. d. D. Forstwiss. *1*, 148–169, 1941.
668. Hesselman, H., Einige Beob. ü. d. Beziehung zw. d. Samenverbreit. v. Fichte u. Kiefer u. d. Besamung d. Kahlhiebe. * Meddel. Fran. Stat. Skogförsöksanst. *27*, 145–182, Stockholm 1934.
669. —, Weitere Studien usw. * Ibid. *31*, 1–64, 1938.
670. Koch, H. G., Temp.verhältn. u. Windsystem e. geschloss. Waldgebiets. * Veröff. Geophys. I. Leipzig *6*, Heft 3, 1934.

670a. —, D. Wald-Feldwind, e. mikro-aerolog. Studie. * Beitr. Phys. d. fr. Atm. *22*, 71–75, 1934.
671. —, D. mikroklim. Temp.feld bei Bewölkung u. Wind. * Biokl. B. *2*, 121–124, 1935.
671a. —, Der Waldwind. * Eine forstmeteorologische Eigenart von Waldgebieten. * Forstwiss. C. *64*, 97–111,1942.
671b. —, Bestandstemperaturen eines bewaldeten Seitentales bei Jena. * Mitt. d. Thüring. Landeswetterwarte Heft 7, 69–98, Weimar 1948.
671c. Lampadius, G., Nebelfrostablagerungen sowie Tau- und Nebelniederschlag. * Thar. Forstl. Jahrb. *92*, 545–584, 1941.
672. Lehmann, H., Mikroklimat. Unters. d. Abkühlungsgrösse in e. Waldgebiet. * Veröff. Geophys. I. Leipzig 7, Heft 4, 1936.
673. Linke, F., Niederschlagsmess. unter Bäumen. * Met. Z. *33*, 140–141, 1916.
674. —, —. * Met. Z. *38*, 277, 1921.
675. Marloth, Ü. d. Wassermengen, welche Sträucher u. Bäume aus treib. Nebel u. Wolken auffangen. * Met. Z. *23*, 547–553, 1906.
676. Pfeiffer, H., Kleinaerolog. Unters. am Collmberg. * Veröff. Geoph. I. Leipzig *11*, Heft 5, 1938.
677. Rubner, K., Bestandsklima u. Verjüngungsverfahren. * Sudetend. F. u. Jagdz. *30*, 353–360, 1930.
678. Rubner, K., D. Nebelniederschlag im Wald u. s. Messung. * Thar. Forstl. Jahrb. *83*, 121–149, 1932.
679. —, — II. * Ibid. *86*, 330–342, 1935.
680. Schimitschek, E., Forstschutzl. u. forstentomolog. Stud. aus d. Demonstrationsrevier Pressbaum d. Hochsch. f. Bodenkultur. * Wien. Allg. F. u. Jagdz. 1932, Nr. 47 & 48.
681. Schmauss, A., Seewinde ohne See. * Met. Z. *37*, 154–155, 1920.
681a. Sigmond, H., Einige Bem. ü. d. Sonderklima d. Lochhiebs. * Sudetend. F. u. Jagdz. *29*, 227–228, 1929.
682. Wagner, C., D. Grundlagen d. räuml. Ordnung im Walde. 4. Aufl. * Berlin, P. Parey, 1923.
683. Woefle, M., Windverhältnisse im Walde. * Forstw. C. *61*, 65–75, 1939, * *61*, 461–475, 1939, and *64*, 169–182, 1942.
683a. —, Bemerkung zu "Der Waldwind" von H. G. Koch. * Forstwiss. C. u. Thar. Forstl. Jahrb. (Kriegsgemeinschaftsausgabe) 1944, 131–136.
684. v. Wrede, C., D. Bestandsklimat. u. ihr Einfluss uf d. Biologie d. Verjüngung unter Schirm u. in d. Gruppe. * Forstw. C. *47*, 441–451, 491–505, 570–582, 1925.

CHAPTER 36. THE ANIMATE WORLD AND THE MICROCLIMATE.

685. Blake, J. H., Further stud. on deciduous forest animals communities. * Ecology *12*, 508–527, 1931.

686. Bodenheimer, F. S., Stud. z. Epidemiologie, Ökol. u. Phys. d. afrik. Wanderheuschrecke. * Z. f. angew. Entomol. *15*, 435–557, 1929.
687. Buxton, P. A., Insects of Samoa. Part. IX, Fasc. 1, * Brit. Mus. London 1930.
688. Eidmann, H., D. Flugzeugbestäubung d. Forstschädl. u. ihre Organis. im Lichte neuzeitl. Erfahr. u. Forsch. * Z. f. F. u. Jagdw. *65*, 24–48, 65–82, 1933.
689. Escherich, K., D. Forstinsekten Mitteleuropas. Bd. 3. * Berlin, P. Parey, 1931.
690. Fränkel, G., Unters. ü. d. Lebensgewohnh., Sinnesphys. u. Sozialpsych. d. wandernden Larven d. afrik. Wanderheuschrecke. * Biolog. Zentralbl. *49*, 657–680, 1929.
691. Franz, H., Ü. d. Bedeutung d. Mikrokl. f. d. Faunenzus.setzung auf kleinem Raum. * Z. Morphol. u. Ökol. d. Tiere *22*, 587–628, 1931.
691a. Gösswald, K., Rassenstudien an der grossen Waldameise auf systematischer ökologischer, physiologischer und biologischer Grundlage. * Z. f. angew. Entomolog. *28*, 62–124, 1941.
692. Grimm, H., Kleintierwelt, Kleinklima u. Mikroklima. * Z. f. angew. Met. *54*, 25–31, 1937.
694. Hesse, R., Tiergeographie auf ökolog. Grundlage. * G. Fischer, Jena, 1924.
695. Himmer, A., E. Beitr. z. Kenntn. d. Wärmehaushalts im Nestbau sozialer Hautflügler. * Z. f. vergl. Physiolog. 5, Nr. 2, 1927.
696. Klemm, M., Neue Wege in d. biolog. Biotopforschung. * Naturf. *6*, 254–260, 1929.
697. Kühnelt, W., D. Bedeutung d. Klimas für d. Tierwelt. * Biokl. B. *1*, 120–125, 1934.
698. —, D. Einfluss d. Klimas auf d. Wasserhaushalt d. Tiere. * Biokl. B. *3*, 11–15, 1936.
699. Lauscher, F., Mückentanz u. Windschutz. * Biokl. B. *6*, 186, 1939.
700. Löhrl, H., D. Winterschlaf v. Nyctalus noctula Schreb. auf Grund v. Beob. am Winterschlafplatz. * Z. Morphol. u. Ökol. d. Tiere *32*, 47–66, 1936.
701. Martini, E. & Hundertmark, A., Ü. d. Bedeutung kleinklimat. Feststell. in Haus u. Stall u. im Freien für d. Schädlingsbiologie. * Anz. f. Schädlingskunde *26*, 97–101, 1940.
702. Martini, E. & Teubner, E., Ü. d. Verhalten v. Stechmücken bei verschied. Temp. u. Luftfeucht. * Beih. z. Archiv f. Schiffs- u. Tropenhyg. *37*, Beiheft 1, 1933.
703. Mosauer, W., The toleration of solar heat in desert reptiles. * Ecology *17*, 56–66, 1936.
704. Nielsen, E. T., Temp. in a nest of Bombus hypnorum L. * Vidensk. Medd. fra Dansk naturh. Foren *102*, 1938.

705. —, Z. Ökologie d. Laubheuschrecken. * Saertryk af Ent. Medd. *20*, 121–164, 1938.
706. Schimitschek, E., Forstentomolog. Unters. a. d. Gebiet v. Lunz I: Standortskl. u. Kleinkl. in i. Bez. zum Entwicklungsablauf u. z. Mortalität v. Insekten. * Z. f. angew. Entomol. *18*, 460–491, 1931.
707. —, — II: * C. f. d. ges. Forstwesen *58*, 225–267, 1932.
708. Steiner, A., Neuere Ergebn. ü. d. sozialen Wärmehaushalt d. einheim. Hautflüger. * Naturw. *18*, 595–600, 1930.
708a. Uvarov, B. P., Wetter u. Klima in ihr. Bez. zu d. Insekten. * Z. f. angew. Entomol. *17*, 157–177, 1930.
709. Warnecke, G., Mikroklima u. Verbreit. d. Lepidopteren. * Entomol. Beih., Berlin-Dahlem *1*, 120–130, 1934.
710. Wellenstein, G., Beitr. z. Biologie d. roten Waldameise m. bes. Berücks. klimat. u. forstl. Verhältn. * Z. f. angew. Entomol. *14*, 1–68, 1929.
711. Wiele, H., Für Hagenbeck im Himalaja. * Deutsche Buchwerkstätten Dresden 1925.
712. Zwölfer, W., Beitr. z. Kenntn. d. Schädlingsfauna Kleinasiens I. * Z. f. angew. Entomol. *17*, 227–252, 1930.
713. —, Stud. z. Ökologie u. Epidemiologie d. Insekten. * Z. f. angew. Entomol. *17*, 475–562, 1931.

Chapters 37 and 39. The Unintentional Effect of Man on the Microclimate. The Conscious Modification of the Microclimate by Man.

713a. Amelung, W. & Landsberg, H., Kernzählungen in Freiluft u. Zimmerluft. * Biokl. B. *1*, 49–53, 1934.
713b. Amelung, W., Künstliches Klima. * Lehrbuch der Bäder und Klimaheilkunde, H. Vogt. J. Springer, Berlin 1940.
714. Amende, H., Exposition, photochem. Ortshelligk., Heliotherapie u. Platzwahl v. Krankenanst. * Strahlentherapie *63*, 115–128, 1938.
715. Bates, C. G., Windbreaks, their influence and value. * Forest Serv. Bull. Nr. 86, U. S. A. (1912?).
715a. Bauer, E., D. Wohlfahrtsaufforst. im Flugsandgeb. d. Marchfelds. * Österr. Viertelj-schr. f. Forstwesen *54*, 103–126, 175–199, 1936.
716. Berké, T. & Castens, G., Z. Kenntn. d. Temp. u. Feucht. d. Schiffsluft. * Ann. d. Hydr. *57*, 169–185, 1929.
717. Bradtke, F. & Liese, W., Hilfsbuch f. raum- u. aussenklimat. Mess. * J. Springer, Berlin, 1937.
718. Brezina, E. & Schmidt, Wilh., D. künstliche Klima. * Stuttgart, F. Enke, 1937.
719. Büttner, K., Physik. Bioklimatologie. Probleme u. Methoden. * Akad. Verl. Ges., Leipzig, 1938.
720. —, D. Bedeutung d. Mikrokl. f. d. Klimadosierung. * Strahlentherapie *61*, 705–710, 1938.

721. Conrad, V. & Hausmann, W., Gesichtspunkte d. medizin. Klimatol. m. bes. Berücks. d. med.-klimat. Akt. d. österr. San. Verwaltung. M. Perles, Wien, 1930.
721a. Dorno, C., Zur Entwicklungsgeschichte der Bioklimatologie * Biokl. B. 9, 4–11, 1942.
722. Egloff, K., Ü. d. Klima im Zimmer u. s. Beziehungen z. Aussenklima. * Diss. Zürich Nr. 766. (1934).
722a. Ehrenberg, P., Landwirtschaftlich beachtliche Windwirkungen und Windschutz in der Landwirtschaft. * Der Kulturtechniker *46*, 19–41, 1943.
723. Fels, E., D. Mensch als Gestalter d. Erde. * Leipzig, Bibliogr. Inst., 1935.
724. Flach, E., D. Bedeutung d. lokalklimat. Forsch. f. d. Meteoropath. d. Erkält.krankh. * Biokl. B. 5, 22–26, 1938.
725. —, D. klimat. Verhältn. in Deutschl. u. d. Abhaltung v. Sommerlagern. * Münchn. Mediz. Wochenschr. 1938, S. 947.
726. Flensborg, C. E., D. dänische Heidegesellschaft. * Viborg 1939.
726a. Flohn, H., Die Tätigkeit des Menschen als Klimafaktor (Sammelreferat). * Z. f. Erdkunde 9, 13–22, 1941.
727. Franssila, M., Ü. d. Windschutzproblem. * Maatal. Aiakakauskirja, Helsinki *11*, 168–182, 1939.
728. Geiger, R., Wald und Windschutz. * Forstw. C. *53*, 760–762, 1931.
729. —, Mikroklimatologie. * Naturw. *21*, 132–137, 1933.
730. —, Forstmeteorolog. Beding. d. Ertragssteigerung. * Raumforsch. u. Raumordnung 2, 591–592, 1938.
731. Götz, F. W. P., Strahl.klima v. Arosa.. Berlin 1926.
732. Gregor, A., E. Beitrag z. Klassifikation d. Mittelgebirgsklimas f. Heilzwecke. * Biokl. B. *6*, 187–191, 1939.
733. —, Ü. met. Voraussetzungen f. d. Charakter Luftkurort (klimatischer Kurort). * Biokl. B. 7, 125–127, 1940.
734. Grunow, J., Wetter- u. Klimabeeinflussung. * Geogr. Wochenschr. 1933, Heft. 9.
735. Harries, H. D., Neue schiffsraum-met. Mess. * Ann. d. Hydr. *61*, 13–18, 1933.
736. Hausmann, W., Grundl. u. Organisation d. lichtklimat. Forsch. in i. Beziehung z. öffentl. Gesundh.pflege. * Mitt. d. Volksgesundh. Amts Wien 1932, Heft 10.
737. Hellpach, W., Geopsyche. D. Menschenseele unterm Einfluss v. Wetter u. Klima, Boden u. Landschaft. 5. Aufl. * Engelmann, Leipzig, 1939.
738. Hottinger, M., D. Raumklima u. s. Regelung. * Gesundh.Ing. *62*, 605–609, 617–622, 1939.
739. Hummel, K., Zum Mikrokl. isolierter Standorte. * D. Met. Jahrb. f. Bayern 1929, Anhang B.

740. Knoch, K., D. Kurortklimadienst d. deutsch. Reichswetterdienstes. * Biokl. B. *5*, 1–3, 1938.
741. —, Ü. d. klimat. Anforderungen an e. Kurort. * Biokl. B. *5*, 103–106, 1938.
742. Koláček, F., D. Einfluss menschl. Tätigk. auf d. klimat. Verhältn. in Mähren usw. * Met. Z. *52*, 114, 1935.
742a. Kreutz, W., Das Windschutzproblem. * Biokl. B. *5*, 10–16, 1938.
742b. —, Agrarmeteorologische Forschungen auf der Hohen Rhön. * Ber. d. Oberhess. Ges. f. Natur-u. Heilkunde zu Giessen *20*, 26–104, 1940.
743. Kroh, A., A micro-climate recorder. * Ecology *21*, 275–278, 1940.
744. Küster, E. & Meixner, H., Berechn. u. Tab. zur Frage d. Raumklimas. * Arch. f. Hyg. *117*, 158–178, 1936.
744a. Landsberg, H., Werkraumluft u. Gewerbekrankh. (Sammelreferat). * Biokl. B. *2*, 35–37, 1935.
745. —, E. Bett.Temp.-Studie. * Biokl. B. *5*, 66–68, 1938.
746. Lehmann, P., Landbautechn. Massnahmen in agrarmet. Betrachtung. * Fortschr. d. Landwirtsch. *5*, 797–806, 1930.
747. —, D. Sonderklima d. Stalles. * Ibid. *6*, 642–647, 1931.
747a. —, Inwieweit berücks. d. Landwirt d. Klimafaktor? * Biokl. B. *7*, 77–85, 1940.
748. Leontiewski, N. P., D. Rolle d. Waldschutzanlagen in bezug auf Steigerung d. Ernte. * J. of Geophysics Leningrad *4*, 139, 1934.
749. Linden, A. J. ter-, D. Winterklima in Gebäuden. * Gesundheits-Ingenieur *61*, 480–483, 1938; D. Sommerklima i. G. Ibid. *61*, 522–526, 1938.
750. Linke, F., Klimat. Anforder. an e. Kurort i. Flachland oder Mittelgeb. Mitteleuropas. * Biokl. B. *5*, 7–9, 1938.
751. —, Z. Physik d. künstl. Klimas. * Der Balneologe *6*, 241–249, 1939.
752. Mäde, A., Ü. d. Temp.gang in Gewächshäusern, Dunkelkästen u. Mistbeetanlagen. * Gartenbauwiss. *14*, 626–641, 1940.
753. Mäde, A. & Rudorf, W., Zweck u. Aufbau modern. bewett. Gewächshäuser u. ihr Temp.gang i. Vergl. m. d. Freiland. * Biokl. B. *5*, 145–153, 1938.
754. Mayer, A., Ü. d. Vermeidung v. Schwitzwasser in Käsekellern. * Milchwirtschaftl. Forsch. *11*, 201–210, 1930.
755. Mehner, A. & Linz, A., Unters. ü. d. Verlauf d. Stalltemp. * Forschungsdienst *8*, 525–543, 1939.
755a. Meyer, F. G., Zimmerklimatische Studien. * Wärme-und Kältetechnik *43*, 41–46 und 173–177, 1941.
755b. —, Zimmerklimatische Studien. * Strahlungstherapie *72*, 347–348, 1943.
756. Michler, H., Z. Kenntn. d. Luftbeweg. in Schiffsräumen. * Ann. d. Hydr. *62*, 457–461, 1934.

757. Mörikofer, W., Klimatolog. Gesichtspunkte f. d. Erricht. v. Krankenhäusern, Sanatorien etc. * Manuscript Davos 1934.
757a. Nägeli, W., Untersuchung über die Windverhältnisse im Bereich von Windschutzstreifen. * Mitt. d. Schweiz. Anst. f. d. forst. Versuchswesen *23*, 223–276, 1943.
757b. Nägeli, W., Weitere Untersuchungen über die Windverhältnisse im Bereich von Windschutzstreifen. * Mitt. Schweiz. Anst. f. d. forstl. Versuchswesen *24*, 659 ff. 1946.
758. Robitzsch, M., Klima u. Organismus. * R. f. W. Wiss. Abh. *1*, *Nr.* 1, 1935. *Wide bibliog. included.*
759. Roose, H., E. neue Methode z. Best. d. Wandtemp. im Raumklima. * Schweiz. Bl. f. Heiz. u. Lüftung 1938.
760. Ruge, H., D. Verhalten d. Lufttemp. u. Luftfeucht. auf e. modernen Kreuzer in d. Tropen. * Veröff. a. d. Geb. d. Marine-Sanit.-Wesens Heft 22. Berlin, Mittler & Sohn, 1932.
761. Scaëtta, H., Bioclimats; climats des associations et microclimats de haute montagne en Afrique Centrale Equat. * J. d'agronomie col. Brüssel, June 1933.
761a. Schnelle, F., D. Einsatz d. Met. bei d. Ödlandkultivierung. * Z. f. angew. Met. *54*, 221–224, 1937.
761b. Schoenichen, W., Lebende Windschutzanlagen. * Pet. Geogr. Mitt. *90*, 273–278, 1944.
762. Schwarz, H., D. Entstehung d. Flugerde in d. Gauen Niederdonau u. Wien. * Manuscript Wien 1940.
762a. Seemann, J., Über die Temperaturverhältnisse in einem bewetterten Tiefkühlgewächshaus. * D. Gartenbauwiss. *17*, 186–192, 1942.
762b. —, Die Temperaturverhältnisse in Gewächshäusern mit wärmeabsorbierenden Glas. * Biokl. B. *10*, 73–76, 1943.
763. Talman, C. F., Überwachtes Innenklima. * Z. f. angew. Met. *48*, 346–347, 1931.
763a. Tichy, H., Grundlagen einer Klimabeschreibung von Kurorten. * Z. f. Met. *1*, 84–87, 1946.
764. Wagner, F., Ü. Temp. an u. im Schiff. * Ann. d. Hydr. *63*, 38–40, 1935.
764a. Wegener, K., D.Temp. im Glas-(Treib-)haus. * Biokl. B. *7*, 109–112, 1940.
764b. —, Haus und Klima. * Z. f. angew. Met. *59*, 1–6, 1942.
765. Weickmann, L., E. Taschenthermohygrograph als bioklim. Forschmittel. * Sitz-B. d. Sächs. Akad. *90*, 47–54, Leipzig 1938.
766. —, Klima u. Wetter im Lebensraum d. Menschen. * Naturw. *27*, 22–28, 1939.
767. Woelfle, M., Wald u. Windschutz (3 Teile). * Forstw. C. *57*, 349–362, 1935; *58*, 325–338, 429–448, 1936.
768. —, Hecken als Windschutzanlagen. * Forstw. C. *60*, 15–28, 1938.
769. —, Windschutzanlagen. * Forstw. C. *60*, 52–63, 73–86, 1938.

770. Woltereck, H., Klima . Wetter . Mensch. * Leipzig, Quelle & Meyer, 1938.
771. Wysotzky, Shelterbelts in the steppes of Russia. * J. of Forestry *33*, No. 9, 1935.

CHAPTER 38. THE CITY CLIMATE.

(A complete bibliography up to year 1936 will be found in the book by A. Kratzer (*781*). Here only later works or those not mentioned there are listed.)

772. Arakawa, H., Increasing daily min. temp. in large, developing cities. * Gerl. B. *54*, 177–178, 1939.
772a. Arnberger, F., Einige Temperatur- und Feuchtigkeitsmesungen in Tripolitanien. * Mitt. Geogr. Ges. Wien *83*, 249–257, 1940.
772b. Berg, H., Die Bewölkungsverhältnisse über der Grosstadt Köln und ihrer Umgebung (eine vergleichende Untersuchung) * Z. f. angew. Met. *60*, 108–117, 1943.
772c. —, Der Einfluss einer Grosstadt auf Bewölkung, Niederschlag und Wind. * Biokl. B. *10*, 65–70, 1943.
773. Bider, M., Temp.untersch. zw. Stadt. u. Freilandstationen. * Helv. Phys. Acta *13*, 5–7, 1940.
774. Brazier, C. E. & Perdereau, L., Exemple d'une altération du climat résultant de l'activité humaine. * La. Mét. *11*, 313–324, 1935.
775. Dörffel, K., D. Stadtklima v. Marburg a. d. L. * Z. f. angew. Met. *53*, 173–180, 1936.
776. Herrig, H., D. Staubverteilung in Marburg a. d. L. * Biokl. B. 5, 49–57, 1938.
777. Hrudička, B., Zu d. opt. u. akust. Eigenschaften d. Klimas e. Grosstadt. * Gerl. B. *53*, 337–344, 1938.
778. Kähler, K. & Brandtner, G., Mess. d. Staubgehalts d. Luft in Bad Tölz. * Biokl. B. *5*, 58–62, 1938.
779. Kassner, C., Schneefall in u. ausserh. d. Grosstadt. * Z. f. angew. Met. *56*, 337–339, 1939.
780. Keil, K., Windrichtung u. Sicht. * Beitr. Phys. d. fr. Atm. *15*, 87–89, 1929.
781. Kratzer, A., Das Stadtklima * (Die Wissenschaft, Bd. 90). Braunschweig, Friedr. Vieweg & Sohn, 1937.
781a. Lammert, W., Beispiel einer extremen Strahlungskälte. * Z. f. Met. *1*, 145–146, 1947.
782. Lauscher, F. & Steinhauser, F., Weitere Unters. in Wien u. Umgeb. * Sitz-B. Wien Akad. *143*, 175–196, 1934.
783. Lessmann, H. & Zedler, P., E. Beitr. z. Berliner Stadtklima. * Biokl. B. *3*, 163–165, 1936.
784. Löbner, A., Horiz. u. vertik. Staubverteilung in e. Grosstadt. * Veröff. Geoph. I. Leipzig 7, Heft 2, 1935.
785. Lossnitzer, H. & Freudenberg, H., Temp.messfahrten im Gebiete d. Stadt Freiburg i. B. * Biokl. B. 7, 30–39, 1940.

786. Metzler, H. K., D. Gang d. rel. Luftfeucht. zwischen Freiland u. Aussenstadt in Hannover. * Biokl. B. *2*, 120–121, 1935.
787. Meyer, E. G., Sonnen- u. Himmelsstrahl. in d. Grosstadt u. im deutsch. Mittelgebirge. * Strahlentherapie *49*, 161–165, 1934.
788. Mrose, H., D. Mühltalwind als Frischluftspender f. d. Jenaer Westviertel. * Z. f. angew. Met. *56*, 377–383, 1939.
788a. Offe, H., Städtehygiene und Mikroklima. * Gesundh.-Ing. *65*, 248–251, 1943.
789. Root, C. J., Airport and city temp. at Detroit, Mich. * M. W. Rev. *67*, 99, 1939.
790. Schmidt, K., Windverhältn. in Freiburg an heit. Sommertagen. * D. Met. Jahrb. f. Baden 1932.
791. Spangenberg, W. W., D. Niederschl.verhältn. in d. Stadt Schwerin i. M. * Z. f. angew. Met. *56*, 205–209, 1939.
792. Voigts, H., Ergebn. v. Kernzählungen in Lübeck-Travemünde. * Biokl. B. *3*, 170–174, 1936.
792a. Weinländer, A., Grosstadt und Klima. * Z. f. angew. Met. *59*, 390–393, 1942.

Chapter 40. Destructive Frost as a Microclimatic Phenomenon.

793. Amann, H., Birkenvorwald als Schutz gegen Spätfröste. * Forstw. C. *52*, 493–502, 581–592, 1930.
794. Batchelor, L. D. & West, F. L., Variation in minimum temp. due to the topography of a mountain valley in its relation to fruit growing. * Utah Agric. Coll. Exp. St. Bull. 141, Utah 1915.
795. Firbas, F., Unters. ü. d. Wasserhaushalt d. Hochmoorpflanzen. * Jahrb. f. wiss. Bot. *74*, 455–696, 1931.
796. Geiger, R., Spätfröste auf d. Frostflächen bei München. * Forstw. C. *48*, 279–293, 1926.
797. Humphreys, W. J., Frost protection. * M. W. Rev. *42*, 562–569, 1914.
798. Lautensach-Löffler, E., D. Sonderklima d. Pfälzer Gebrüchs. * Mitt. d. Pollichia *8*, 90–124, 1940.
799. Münch, E. & Liske, F., D. Frostgefährdung d. Fichte in Sachsen. * Thar. Forstl. Jahrb. *77*, 97–115, 129–148, 161–176, 197–221, 1926.
800. Sauberer, F., Ü. d. Entstehung d. Grasfrostes. * Biokl. B. *4*, 174–177, 1937.
801. Schmauss, A., Gerichtete Frostschäden. * Biokl. B. *6*, 187, 1939.
802. Schubert, J., Kalte Juninächte in Norddeutschl. u. d. Frostschutz im Walde. * Forstarchiv *8*, 225–228, 1932.
803. —, Kälterückfälle u. Nachtfröste. Wind-, Wasserdampf- u. Waldeinfluss. * Met. Z. *57*, 406–410, 1940.
804. Staudacher, D. Frostschäden im Forstbetriebe, deren Ursachen u. Bekämpfung. * Forstw. C. *46*, 1–13, 54–66, 98–111, 1924.
805. Tacke, B., Frosterschein. auf Moorboden. * Biokl. B. *2*, 86–88, 1935.

806. Ziobrowski, S., Ü. d. Einfluss d. harten Winters 1928/29 auf d. Holzgewächse im Rabaflusstale. * Act. Soc. Bot. Poloniae 10, 49–111, 1933.

CHAPTER 41. THE BATTLE AGAINST DESTRUCTIVE FROST.

(A rich bibliography up to 1939 will be found in the book by O. W. Kessler and W. Kaempfert (*813*). Here only later publications or those not there listed are included.)

807. Amann, H., Unters. ü. d. thermische Wirkung v. Schutzgittern in Pflanzgärten. * Forstw. C. *51*, 249–251, 1929.
808. Bender, K., D. Frühjahrsfröste an d. Unterelbe u. ihre Bekämpfung. * Z. f. angew. Met. *56*, 273–289, 1939.
809. Brooks, F. A., Engineering factors involved in orchard heating. *Mechanical Engineering 1938, S. 677–681.
810. Foss, H., Nattefrost. * Landbrukdirekt. Arsberetning 1928, Oslo 1929.
811. Huber, H., Diesjähr. Erfahrungen m. wasserdichten Papier-Frostschirmen. * Schweiz. Z. f. Obst- u. Weinbau *45*, 320–321, 1936.
812. Kadner, T., Nachtfröste, ihre Entstehung, Voraussage u. Abwehr. * Z. f. angew. Met. *52*, 164–167, 1935.
813. Kessler, O. W. & Kaempfert, W., D. Frostschadenverhütung. * R. f. W. Wiss. Abh. *6*, Nr. 2, 1940.
814. Papaioannou, J., D. mikroklimat. Verhältn. unter Pflanzendecken aus Stoff. * Forstw. C. *54*, 666–671, 1932.
815. —, D. Temp.verhältn. unter Pflanzenschutzvorricht. in Forstgärten. * Forstw. C. *56*, 769–782, 1934.
816. Sauberer, F., Einige Unters. ü. Nachtfrost u. Frostschutz in Weingärten. * Biokl. B. *4*, 19–22, 1937.
817. Schmidt, Wilh., Met. Feldversuche ü. Frostabwehrmittel. * Anhang Jahrb. d. Zentralanst. f. Met. Wien 1927, Wien 1929.
817a. Schonnopp, G., Frostschutz durch Beregnung. * Die Technik in der Landwirtschaft 22, 64–67, 1941.
818. Schoonover, W. R. & Brooks, F. A., The smokiness of oil-burning orchard heaters. * Univ. of California Bull. 536, Berkeley, Aug. 1932.
819. Schoonover, W. R., Hodgson, R. W. & Young, F. D., Frost protection in California orchards. * Calif. Agric. Extens. Serv. Circ. 40, 1930.
820. Schoonover, W. R., Brooks, F. A. & Walker, H. B., Protection of orchards against frost. * Ditto Circ. 111, 1939.
821. Sherouse, R. T., Frost protection of ferns by sprinkler irrigation. * M. W. Rev. *67*, 61–62, 1939.
821a. Weger, N., Die Frostschadenverhütung in der Landwirtschaft. * Met. Rundschau *1*, 29–38, 1947.

SOURCES OF ILLUSTRATIONS

FIG. 22. Beitr. z. Physik d. freien Atmosphäre 21 (1933), Fig. 1 on p. 130. Akad. Verl.-Ges. Leipzig.

FIG. 23. ————, Fig. 3 on p. 132.

FIG. 26. Gerl. Beitr. z. Geophysik 49 (1937), Fig. 6 on p. 418. Akad. Verl.-Ges., Leipzig.

FIG. 29. ———— 47 (1936), Fig. 5 on p. 382.

FIG. 30. ————, ————, Fig. 18 on p. 398.

FIG. 31. ————, ————, Fig. 16 on p. 397.

FIG. 52. Anh. z d. Jahrb. d. Zentralanstalt f. Meteorologie Vienna 1927 (Wien 1929), Fig. 12 on p. 25. In commission with Gerold & Co.

FIG. 55. Jahrb. f. wissensch. Botanik 80 (1934), Fig. 5 on p. 343. Verl. Gebr. Borntraeger, Berlin.

FIG. 63. Ann. d. Hydrographie 62 (1934), Fig. 3 and 4 from Table 46. Verl. d. Deutschen Seewarte, Hamburg.

FIG. 64. Gerl. Beitr. z. Geophysik 42 (1934), Fig. 3 on p. 374. Akad. Verl.-Ges., Leipzig.

FIG. 73. Strahlentherapie 54 (1935), Fig. 3 on p. 169. Verl. Urban & Schwarzenberg, Berlin.

FIG. 74. Veröff. d. Geophysikal. Inst. d. Univ. Leipzig. Band VIII, Heft 2, Fig. 8 on p. 91. Published by the author.

FIG. 82. Forstwissensch. Centralblatt 58 (1936), Fig. 1 on p. 108. Verl. Paul Parcy, Berlin.

FIG. 89. Die Naturwissenschaften 18 (1930), Fig. 2 on p. 368. Verl. J. Springer, Berlin.

FIG. 94. Forstwissensch. Centralblatt 56 (1934), Fig. 2 on p. 359. Verl. Paul Parey, Berlin.

FIG. 97. Gerl. Beitr. z. Geophysik 52 (1938), Fig. 4b on p. 439. Akad. Verl.-Ges., Leipzig.

FIG. 98. Beitr. z. Physik d. freien Atmosphäre 21 (1934), Fig. 16 on p. 266. Akad. Verl.-Ges., Leipzig.

FIG. 99. Forstwissensch. Centralblatt 49 (1927), Fig. 11 on p. 919. Verl. Paul Parey, Berlin.

FIG. 104. ———— 57 (1935), Fig. 1 on p. 238.

FIG. 105. Die Naturwissenschaften 21 (1933), Fig. 5 on p. 135. Verl. J. Springer, Berlin.

FIG. 110. Handb. d. Klimatologie, edited by W. Köppen and R. Geiger, Band I, Fig. 13 on p. 26. Verl. Gebr. Borntraeger, Berlin.

FIG. 112. Forstwissensch. Centralblatt 55 (1933), Fig. 1 on p. 583. Verl. Paul Parey, Berlin.

FIG. 115. ———— 55 (1933), Fig. 3 on p. 744.

FIG. 116. ———— 56 (1934), Fig. 1 on p. 466.

FIG. 117. Gerl. Beitr. z. Geophysik 52 (1938), Fig. 4a on p. 439. Akad. Verl. Ges., Leipzig.

FIG. 124. Jahrb. f. wissensch. Botanik 84 (1937), Fig. 9 on p. 697. Verl. Gebr. Borntraeger, Berlin.

FIG. 125. Beihefte z. Botan. Centralblatt 52 (1934), Part B, Fig. 10 on p. 359. Verl. C. Heinrich, Dresden.

FIG. 142. Gerl. Beitr. z. Geophysik 49 (1937), Fig. 8 on p. 422. Akad. Verl.-Ges., Leipzig.

FIG. 146. Zeitschr. f. Forst- und Jagdwesen 72 (1940), Fig. 4 on p. 157. Verl. J. Springer, Berlin.

FIG. 150. Forstwissensch. Centralblatt 54 (1932), Fig. 28 on p. 382. Verl. Paul Parey, Berlin.

FIG. 151. ————, Fig. 29 on p. 383.

FIG. 159. Veröff. d. Geophysikal. Inst. d. Univ. Leipzig. Band VI, Heft 3, Fig. 5 in Appendix. Published by the author.

FIG. 168. Forstwissensch. Centralblatt 57 (1935), Fig. 2 on p. 792. Verl. Paul Parey, Berlin.

FIG. 170. K. Escherich, Die Termiten oder weissen Ameisen, 1909, Fig. 27 on p. 82. Verl. Dr. Werner Klinkhardt, Leipzig.

FIG. 171. Veröff. d. Geophysikal. Inst. d. Univ. Leipzig, Band VII, Heft 2, Fig. 4 in the Table. Published by the author.

FIG. 174. ————, Band X, Fig. 4 on p. 129.

FIG. 175. Forstwissensch. Centrallbatt 60 (1938), Fig. 10 on p. 82. Verl. Paul Parey, Berlin.

FIG. 178. Reichsamt für Wetterdienst. Wissensch. Abh., Band VI, Nr. 2 (1940), Fig. 55 on p. 84. Verl. J. Springer, Berlin.

FIG. 180. Reichsamt für Wetterdienst. Wissensch. Abh., Band VI, Nr. 2 (1940), Fig. 198 on Plate 7.

FIG. 181. ———— Fig. 100 on p. 178.

INDEX OF AUTHORS

INDEX OF SUBJECTS